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US ARMY
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TEST REPORT OF THE DIRECT STRIKE LIGHTNING TEST OF THE MCC-1 THERMAL PROTECTION SYSTEM (TPS) COATED ALUMINUM PANELS

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19 May 1995

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (LEAVE BLANK)

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED

Final Technical Jan 95

4. TITLE AND SUBTITLE

Test Report of the Direct Strike Lightning Test of the MCC-1 Thermal Protection System (TPS) Coated Aluminum Panels

5. FUNDING NUMBERS

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (MAXIMUM 200 WORDS)

This report details the test results of the direct strike lightning test on the MCC-1 TPS coated aluminum panels.

14. SUBJECT TERMS

Lightning
MCC-1
Thermal Protection System (TPS)

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

DISPOSITION FORM
For use of this form, see AR 340-15: the proponent agency is TAGO.

REFERENCE OR OFFICE SYMBOL	SUBJECT Initial, OPSEC, and Patent Applicability Reviews

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PART I - INITIAL REVIEW
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The attached information, Test Report of the Direct Strike Lightning Test of the MCC-1 TPS Coated Al Panels has been reviewed in Redstone Technical Test Center by Jeffery D. Craven and determined to be factual and unclassified.

Jeffery D. Craven

17 March 1995
DATE

PART II - OPSEC REVIEW
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The attached information, TEST RPT OF THE DIRECT STRIKE LIGHTNING TEST OF THE MCC-1 TPS COATED AL PANELS has been given an OPSEC reviewed in REDSTONE TECH'L TEST CENT by CARL E. ROBERTS and determined to be unclassified, nonsensitive, and suitable for public release.

Carl E. Roberts

7/19/95
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PART III - PATENT APPLICABILITY REVIEW
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The attached information, Test Report of the Direct Strike Lightning Test of the MCC-1 TPS Coated Al Panels has been reviewed for patent applicability, in Redstone Technical Test Center by Jeffery D. Craven. The information

(X) appears to contain no patentable material.
( ) appears to contain patentable material.

( ) patent disclosure has been submitted.
( ) patent disclosure should be submitted.

Jeffery D. Craven

17 March 1995
DATE

DA FORM AUG 90 2496 PREVIOUS EDITIONS WILL BE USED U.S. Government Printing Office: 1983-496-861

EXECUTIVE SUMMARY

This report presents the test procedures and results of the direct strike lightning effects test on the Marshall Convergent Coating -1 (MCC-1) Thermal Protection System (TPS) coated aluminum frustum and aft skirt panels.

The objective of this test effort was to subject the MCC-1 TPS coated frustum and aft skirt panels to the specified direct strike lightning current environment and then ascertain the structural effects of direct strike lightning on the frustum and aft skirt panels.

All of the panels experienced loss of MCC-1 TPS coating at the point of discharge due to the application of the high current (Component A) direct strike lightning environment. The amount of MCC-1 TPS coating loss varied from panel to panel and seemed to depend on how well the material was bonded to the aluminum panel. The application of the intermediate current (Component B) and the continuing current (Component C) direct strike lightning environments resulted in a small melted spot on the aluminum panels with no additional loss of MCC-1 TPS coating. The application of the restrike current (Component D) direct strike lightning environment resulted in slight blackening of the MCC-1 TPS coating around the area of the discharge point with, again, no additional loss of MCC-1 TPS coating.

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I. INTRODUCTION

This report presents the test procedures and results of the direct strike lightning test conducted on the Marshall Convergent Coating -1 (MCC-1) Thermal Protection System (TPS) coated aluminum frustum and aft skirt panels. The test was conducted during January 1995 at the Hazardous Effects Lightning Simulator (HELS) Test Facility located within Test Area 5 of Redstone Arsenal. The test was conducted by personnel of the Electromagnetic Environmental Effects (E^3) Test Branch, Electro-Mechanical Test Division, Redstone Technical Test Center (RTTC).

II. TEST OBJECTIVE

The objective of this test effort was to subject the MCC-1 TPS coated frustum and aft skirt panels to the specified direct strike lightning current environment and then ascertain the structural effects of direct strike lightning on the frustum and aft skirt panels. This effort did not assess the indirect effects of lightning from a direct strike, nor near strike, lightning event on the frustum or aft skirt panels.

III. TEST ENVIRONMENT

The environments required for this test effort were for Zone 1B type lightning strikes as specified in MIL-STD-1757A. Since the objective of this test effort is to determine the structural effects of direct strike lightning on the frustum and aft skirt panels, Test Method T02 of MIL-STD-1757A was utilized to test lightning current waveform Components A, B, C, and D. The requirements for these lightning current waveform components are defined in Figure 1.

IV. EVALUATION CRITERIA

As the objective of this test was data collection, there were no set pass or fail criteria.

V. TEST RESPONSIBILITY

A. REDSTONE TECHNICAL TEST CENTER

The RTTC was responsible for planning and conducting all tests, coordinating and scheduling test facilities, establishing and applying security and safety procedures, providing system instrumentation and test fixtures, modifying test hardware as required, collecting and analyzing test data, and providing a final report or report letter.

B. UNITED TECHNOLOGIES CORPORATION/UNITED STATES BOOSTER INCORPORATED

United Technologies Corporation/United States Booster Incorporated (UTC/USBI) was responsible for providing overall coordination of the test program, including, but not limited to, supplying technical assistance, identifying and providing all test hardware, and support hardware, and for the evaluation of the frustum and aft skirt panels with respect to space shuttle flight safety and crew hazard.

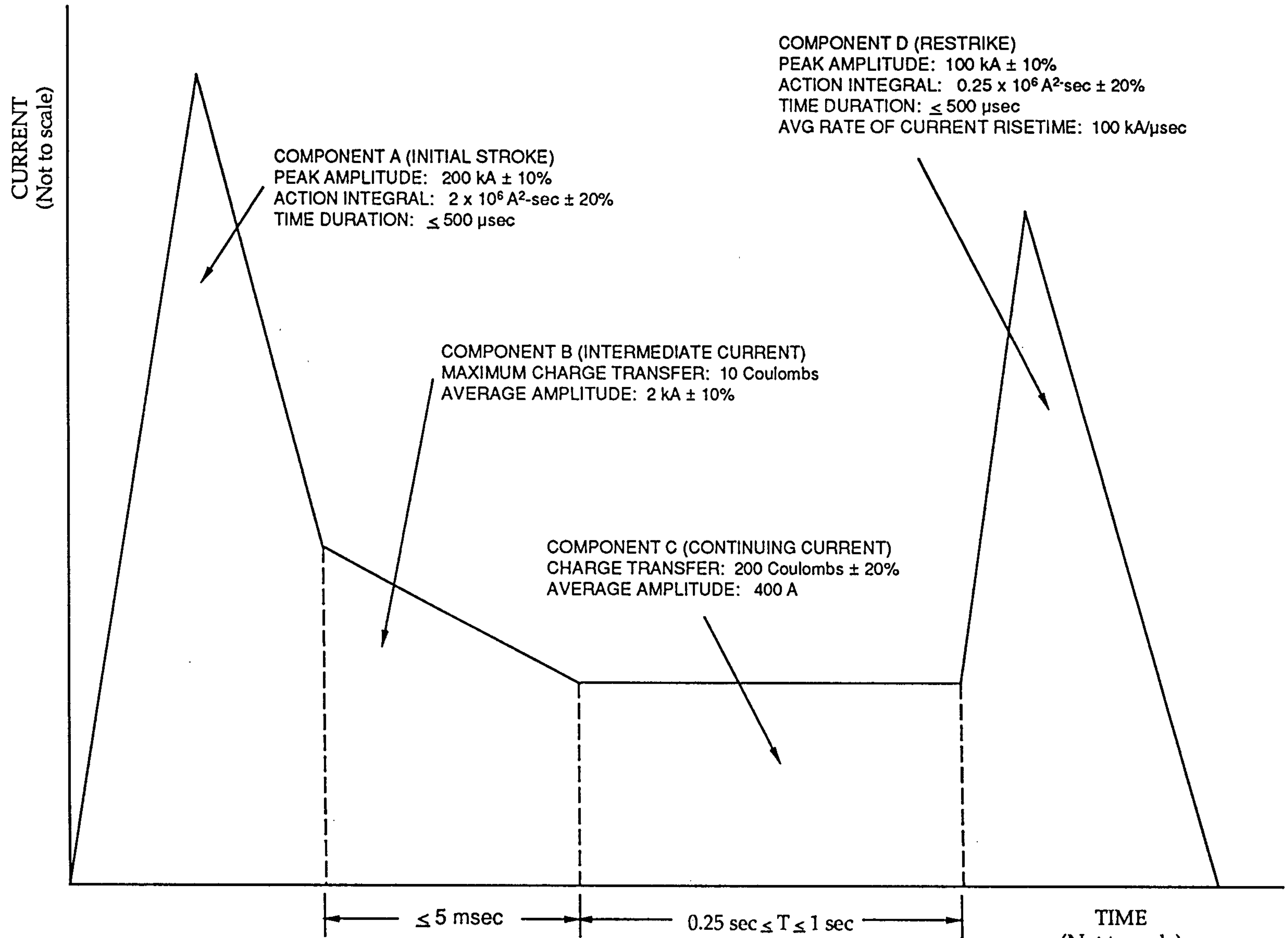


Figure 1. Idealized Direct Strike Lightning Waveform.

C. GEORGE C. MARSHALL SPACE FLIGHT CENTER

George C. Marshall Space Flight Center (MSFC), National Aeronautics and Space Administration (NASA), was responsible for providing the funds for this test program.

VI. FACILITIES AND EQUIPMENT REQUIREMENTS

This section describes the test hardware, facility, and instrumentation utilized to conduct the direct effects lightning test of the MCC-1 TPS coated aluminum frustum and aft skirt panels.

A. TEST HARDWARE

The test hardware was provided by UTC/USBI and consisted of six frustum panels and six aft skirt panels coated with MCC-1 TPS (Figure 2). Three of the frustum panels, as well as three of the aft skirt panels, were provided for calibration purposes.

B. FACILITY

This section describes the various components comprising the simulated direct strike lightning equipment of the Hazardous Lightning (HELS) Test Facility.

1. HIGH CURRENT CAPACITOR BANK

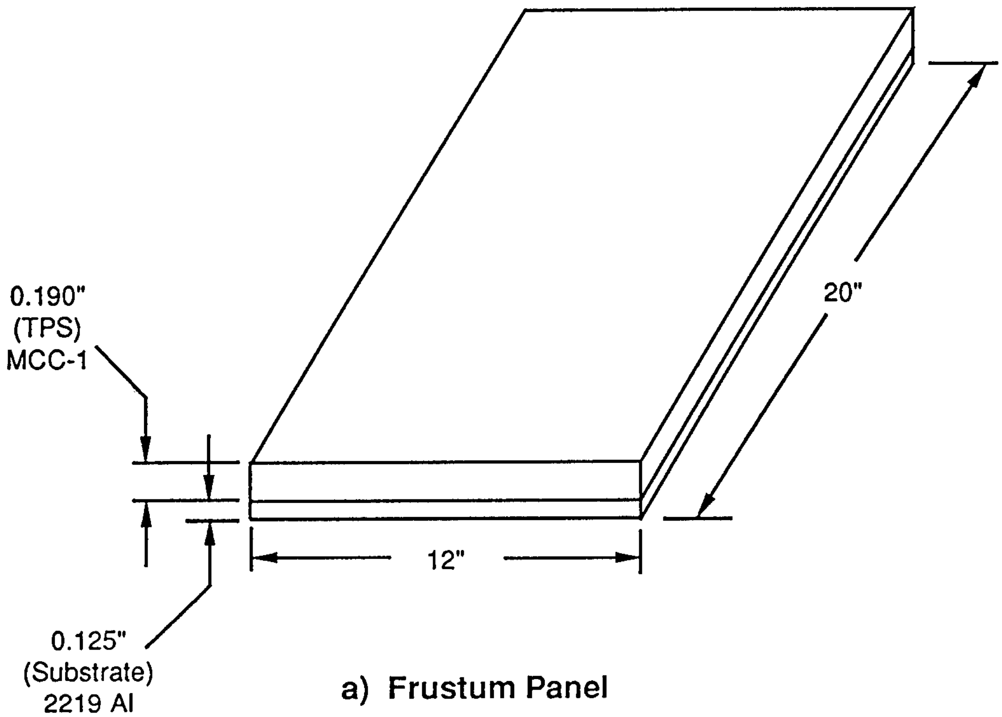
The high current (Component A) capacitor bank consists of 480 capacitors, each rated at 60 kV and 1.875 mF, configured as a two-stage Marx bank with a total capacitance of 56.25 mF and an output voltage of 220 kV. A 2.25 μF, 300 kV peaking capacitor circuit is utilized in conjunction with the high current capacitor bank to increase the current rate-of-rise time to 6.5 msec. The high current capacitor bank can generate a 200 kA ± 10% peak current simulated Component A direct strike lightning waveform with an action integral of 2.0×10^6 A^2sec ± 20% (Figure 3).

2. INTERMEDIATE CURRENT CAPACITOR BANK

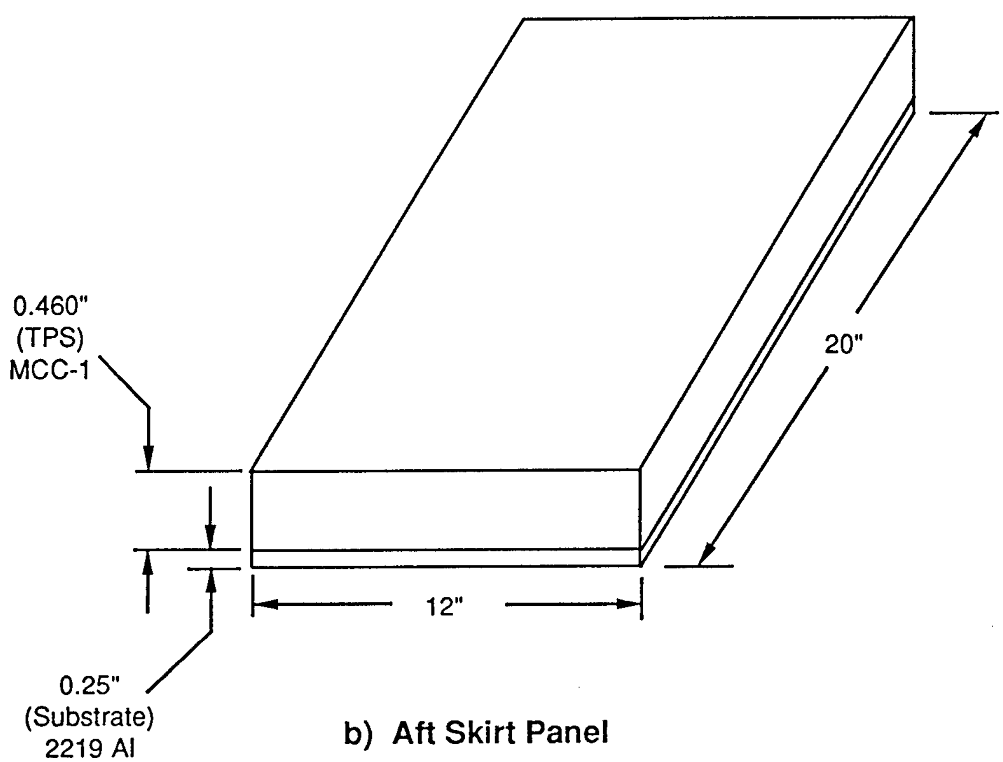
The Intermediate Current (Component B) Capacitor Bank consists of 5 layers of electrolytic capacitors connected in series. Each layer contains 8, 450 volt, 3000 μF capacitors in parallel. The total calculated capacitance is 4800 μF. The charge voltage is 2100 V. The intermediate current capacitor bank can generate a 2000 A 10% simulated direct strike Component B waveform with a peak current of approximately 5800 A and 10 Coulombs (C) of charge transfer (Figure 4).

3. CONTINUING CURRENT CAPACITOR BANK

The Continuing Current (Component C) Capacitor Bank consists of two layers of electrolytic capacitors connected in series. Each layer contains 196, 450 volt, 3000 μF capacitors in parallel. The total measured capacitance is 0.37 F when charged to a nominal value of 750 V. The continuing current capacitor bank can generate a simulated Component C waveform with 200 C ± 20% of charge transfer (Figure 5).

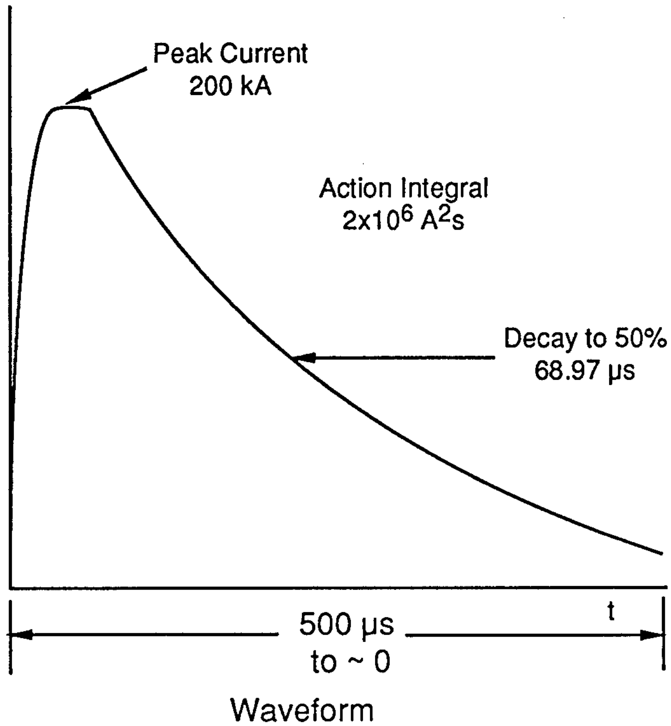


a) Frustum Panel



b) Aft Skirt Panel

Figure 2. Lightning Test Panel Configurations



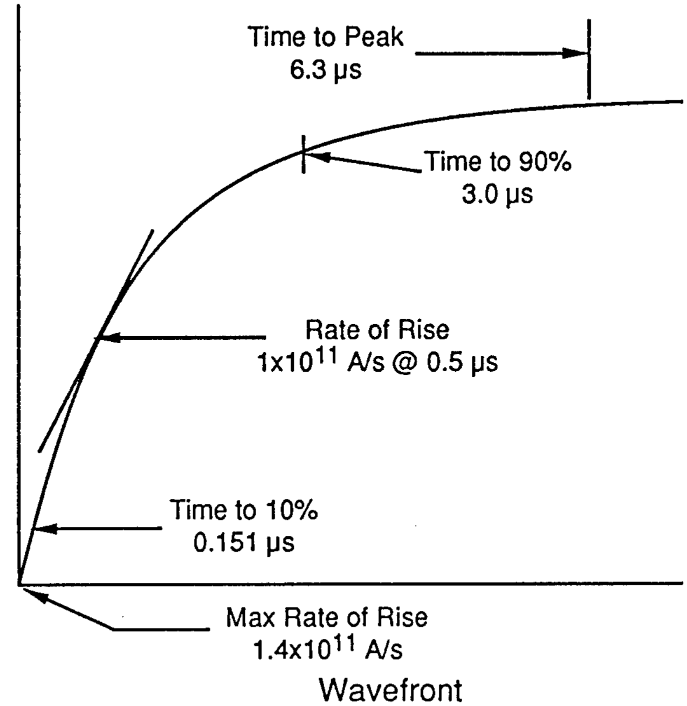


Figure 3. Component A

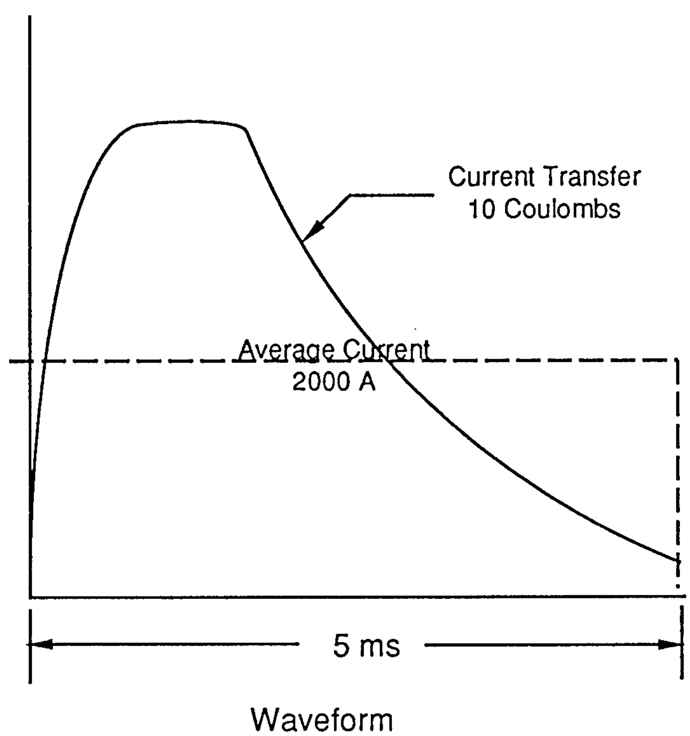


Figure 4. Component B

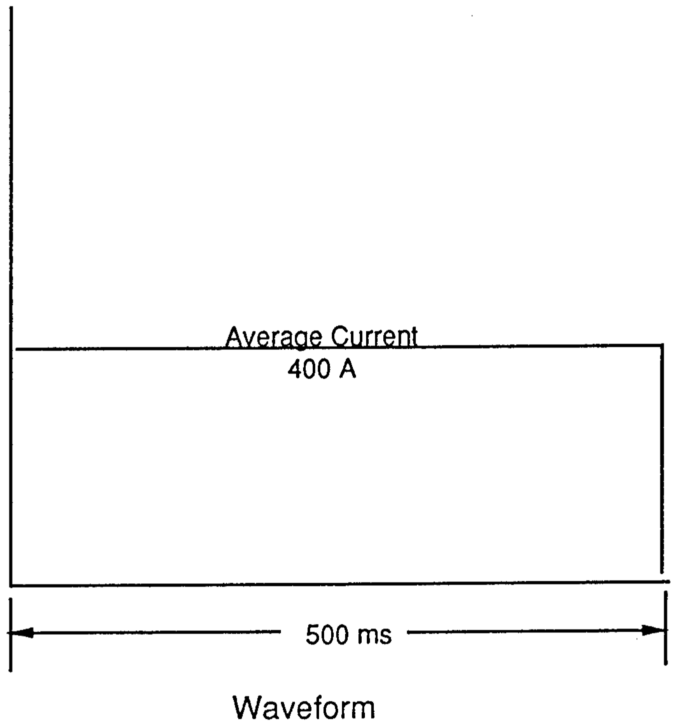


Figure 5. Component C

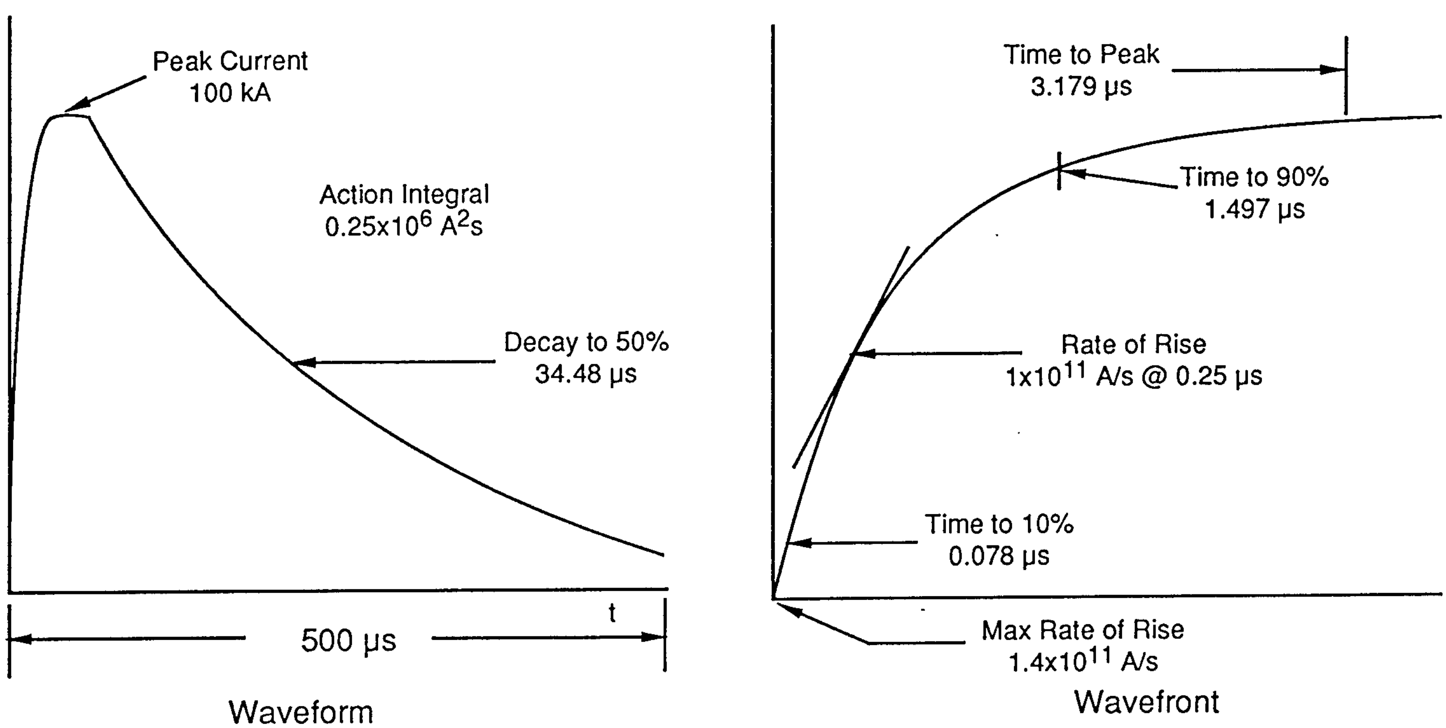


Figure 6. Component D

4. HIGH VOLTAGE RESTRIKE MARX CAPACITOR BANK

The High Voltage Restrike Marx (Component D) Capacitor Bank is an 18 stage Marx bank with a total capacitance of 0.9375 μF. Each stage, consisting of nine 60 kV, 1.875 μF capacitors in parallel, is normally charged to 42 kV to provide a total output voltage of 756 kV. Energy from the Marx bank is delivered to the peaking capacitor/spark gap assembly via an one-inch insulated conductor. The peaking capacitor bank has a total capacitance of 0.027 μF and a maximum voltage capability of 2.2 megavolts. The peaking capacitor bank consists of two parallel stacks of Maxwell capacitors. Each stack contains twenty-two 0.3 mF, 100 kV capacitors in series. The high voltage restrike Marx capacitor bank can generate a 100 kA ± 10% peak current simulated Component D waveform with an average current rate-of-rise of 1.0×10^{11} A/sec and a maximum current rate-of-rise of 1.4×10^{11} A/sec ± 20% (Figure 6).

C. TEST INSTRUMENTATION

The objective of the test effort was to subject the frustum and aft skirt panels to a simulated direct strike lightning test to determine the direct effects only; therefore, only the injection current waveforms are necessary to monitor to insure compliance with the simulated direct strike lightning environment criteria. Instrumentation of the frustum or aft skirt panels were not necessary.

1. HIGH CURRENT INSTRUMENTATION

A Pearson Model 1080 Current Probe is utilized as the sensor for the high current waveform measurement. The current probe is installed on the ground return of the High Current/Continuing Current Discharge Probe. The high current waveform measurement is telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal is recorded on a Hewlett-Packard Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

2. INTERMEDIATE CURRENT INSTRUMENTATION

A Pearson Model 301X Current Probe is utilized as the sensor for the high current waveform measurement. The current probe is installed on the center conductor of the Intermediate Current Discharge Probe. The intermediate current waveform measurement is telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal is recorded on an HP 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

3. CONTINUING CURRENT INSTRUMENTATION

A 0.12 Ohm series resistor is utilized as the sensor for the continuing current waveform measurement. The resistor is installed in-line with the continuing current transmission line. The continuing current waveform measurement is telemetered via a Meret Model MDL281-4-C Fiber Optic System. The signal is recorded on an HP 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

4. HIGH VOLTAGE RESTRIKE INSTRUMENTATION

A Pearson Model 1080 Current Probe is utilized as the sensor for the high voltage restrike waveform measurement. The current probe is installed on the center conductor of the High Voltage Restrike Down Conductor. The high voltage restrike waveform measurement is telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal is recorded on an HP Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

VII. TEST PROCEDURE

The frustum and aft skirt panels were subjected to the simulated direct strike lightning environment described in Figure 1 to determine the structural effects of direct strike lightning on the frustum and aft skirt panels. The direct effects lightning test was divided into four phases: high current test; intermediate current test; continuing current test; and high voltage restrike test.

A. GENERAL TEST PROCEDURES

Operating procedures for the HELS facility are described in the "Hazardous Test Procedures For High Energy Lightning Simulator (HELS), AMSMI-RD-S-H-6", May 1987, and the associated Addendum dated 26 August 1988. The following is a general test procedure that was followed for each test sequence:

1. Perform pretest calibration of the simulated direct strike lightning generators on a frustum calibration panel.

2. Bolt a frustum test panel onto the ground return plate of the test fixture.

3. Install instrumentation and set up the high current (Component A) lightning generator and associated test equipment. Figures 7, 8, and 9 illustrate the test setup for the high current lightning test.

4. Charge high current lightning generator.

5. Initiate video recording sequence.

6. Discharge to the center portion of the frustum panel.

7. Record test data (Appendix C).

8. Repeat steps 2 through 7 for the remaining two frustum test panels.

9. Repeat steps 1 through 8 for the three aft skirt test panels.

10. Repeat steps 1 through 9 for the intermediate current (Component B) lightning generator. Figures 10, 11, and 12 illustrate the test setup for the intermediate current lightning test.

11. Repeat steps 1 through 9 for the continuing current (Component C) lightning generator. The test setup for the continuing current lightning test was identical to the test setup for the high current lightning test (see Figures 7, 8, and 9) except the discharge probe was positioned 0.25 inches from the panel.

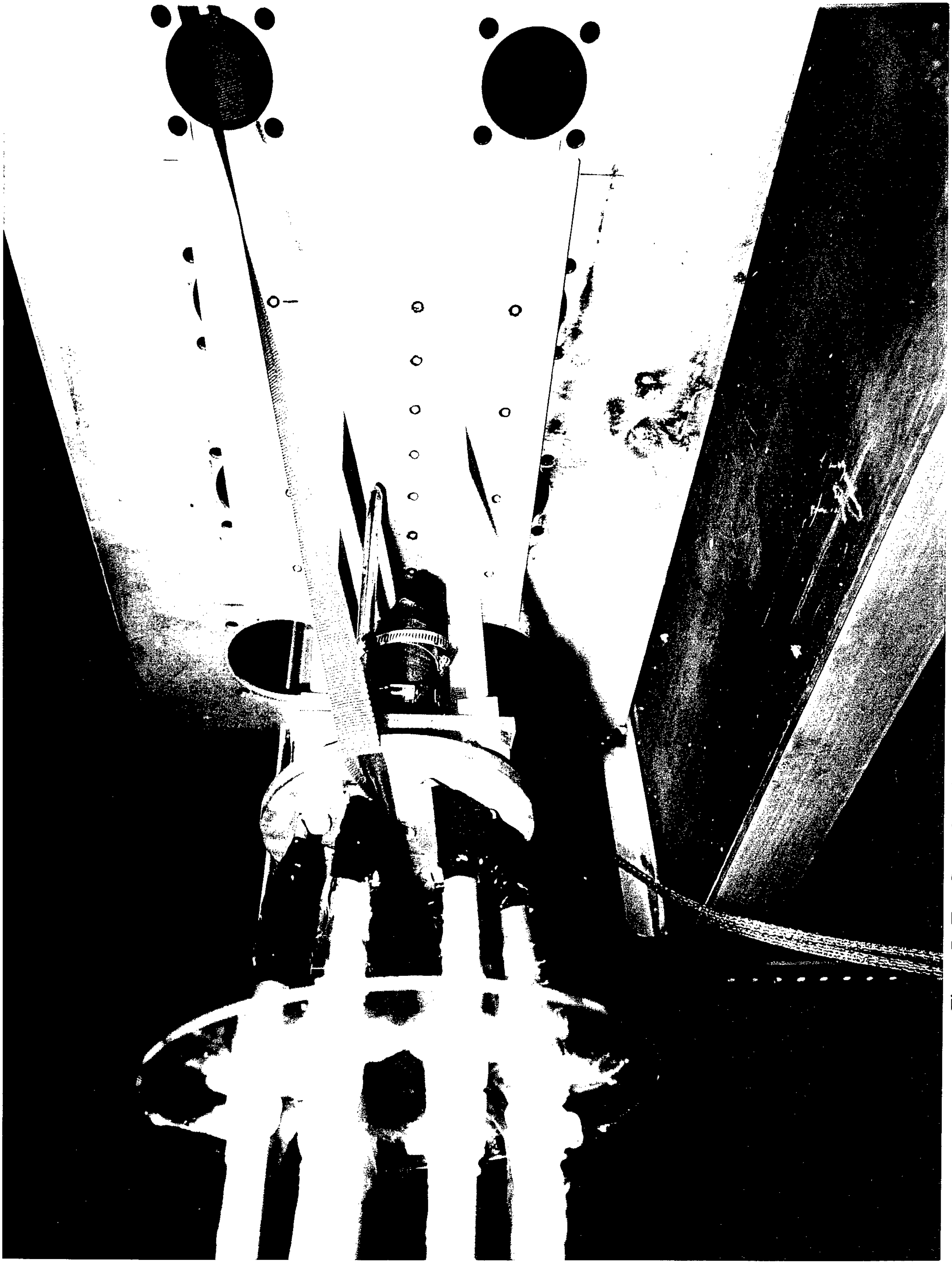


Figure 7. Test Setup for High Current and Continuing Current Lightning Tests.

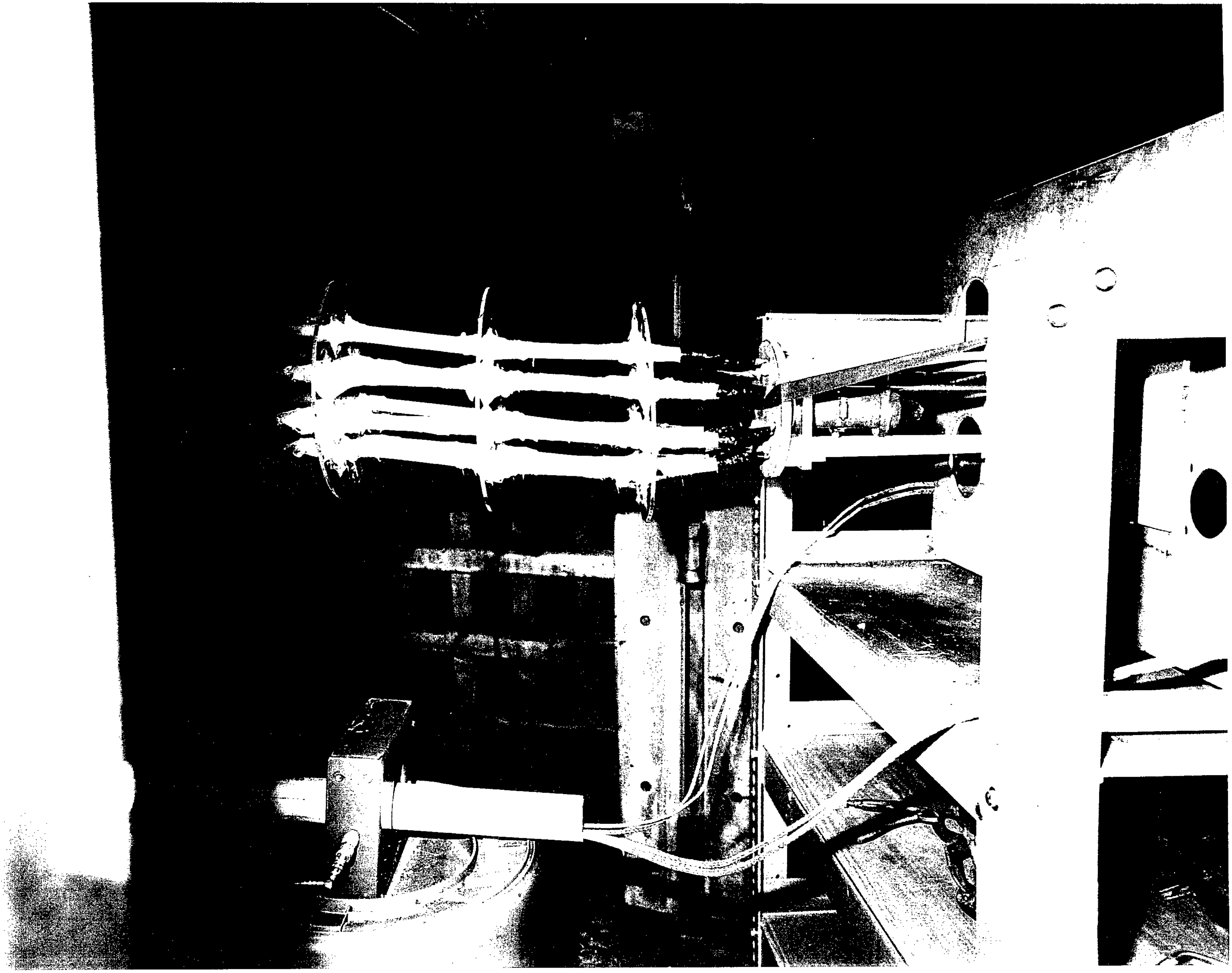


Figure 8. Test Setup for High Current and Continuing Current Lightning Tests.

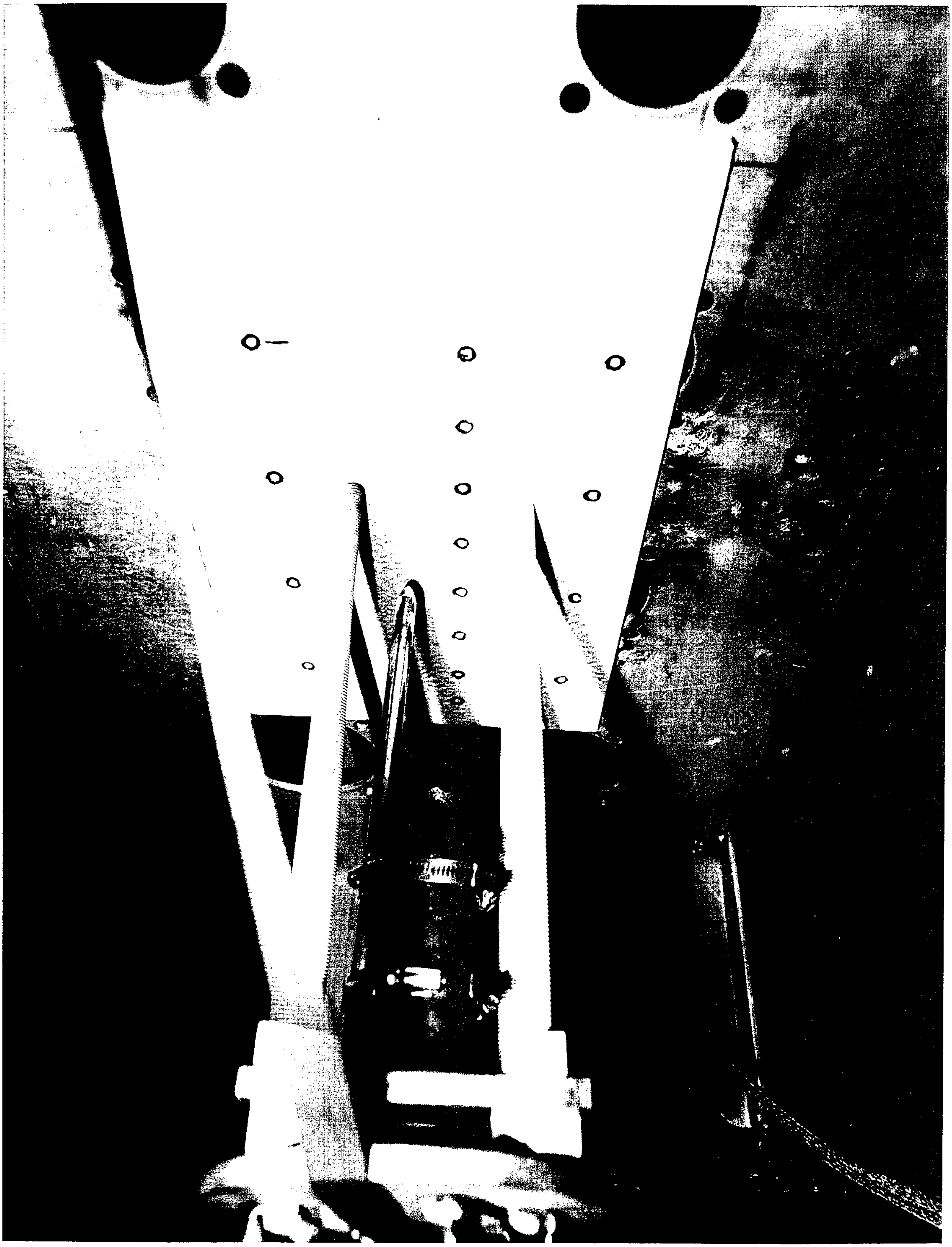


Figure 9. Test Setup for High Current and Continuing Current Lightning Tests.

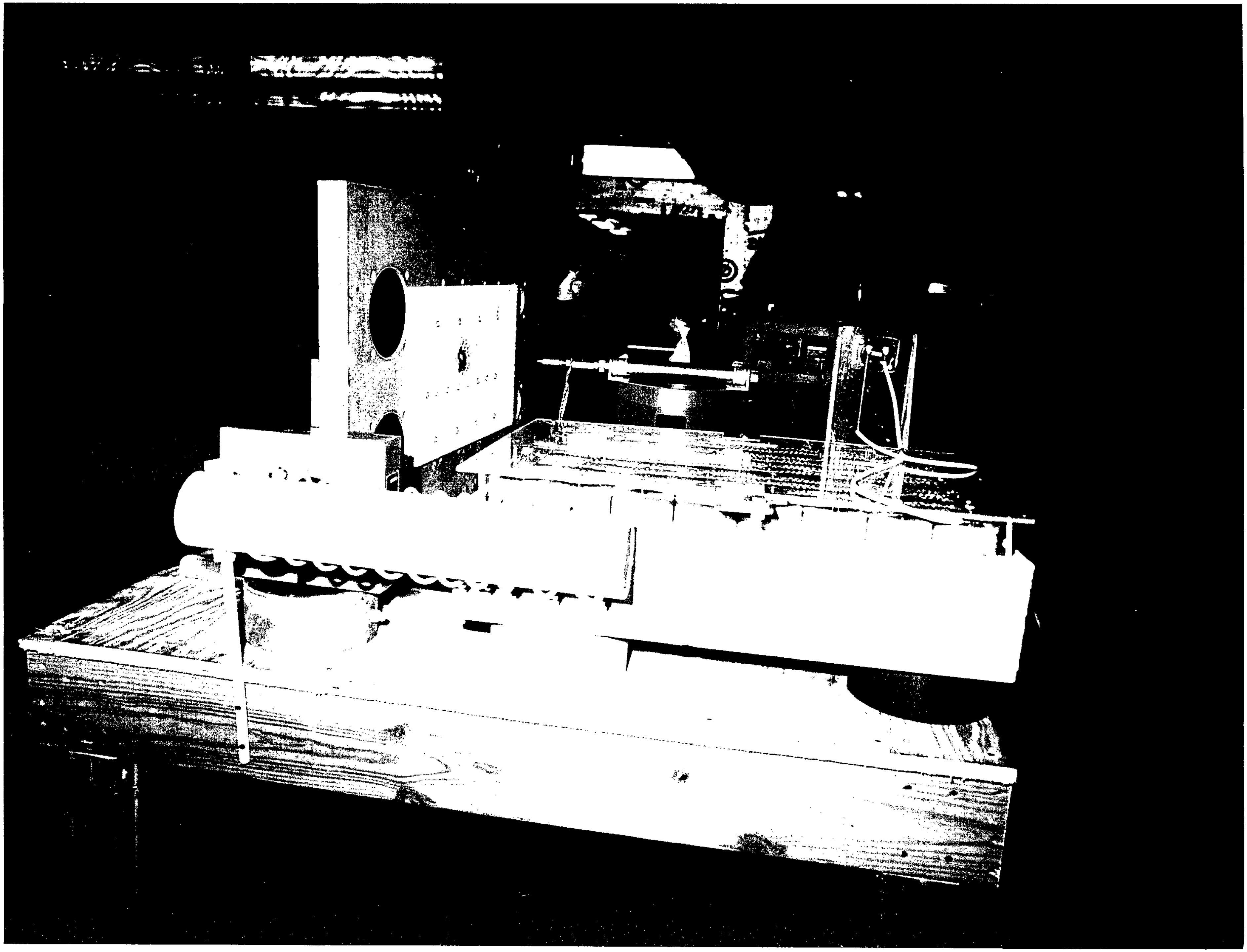


Figure 10. Test Setup for the Intermediate Current Lightning Test.

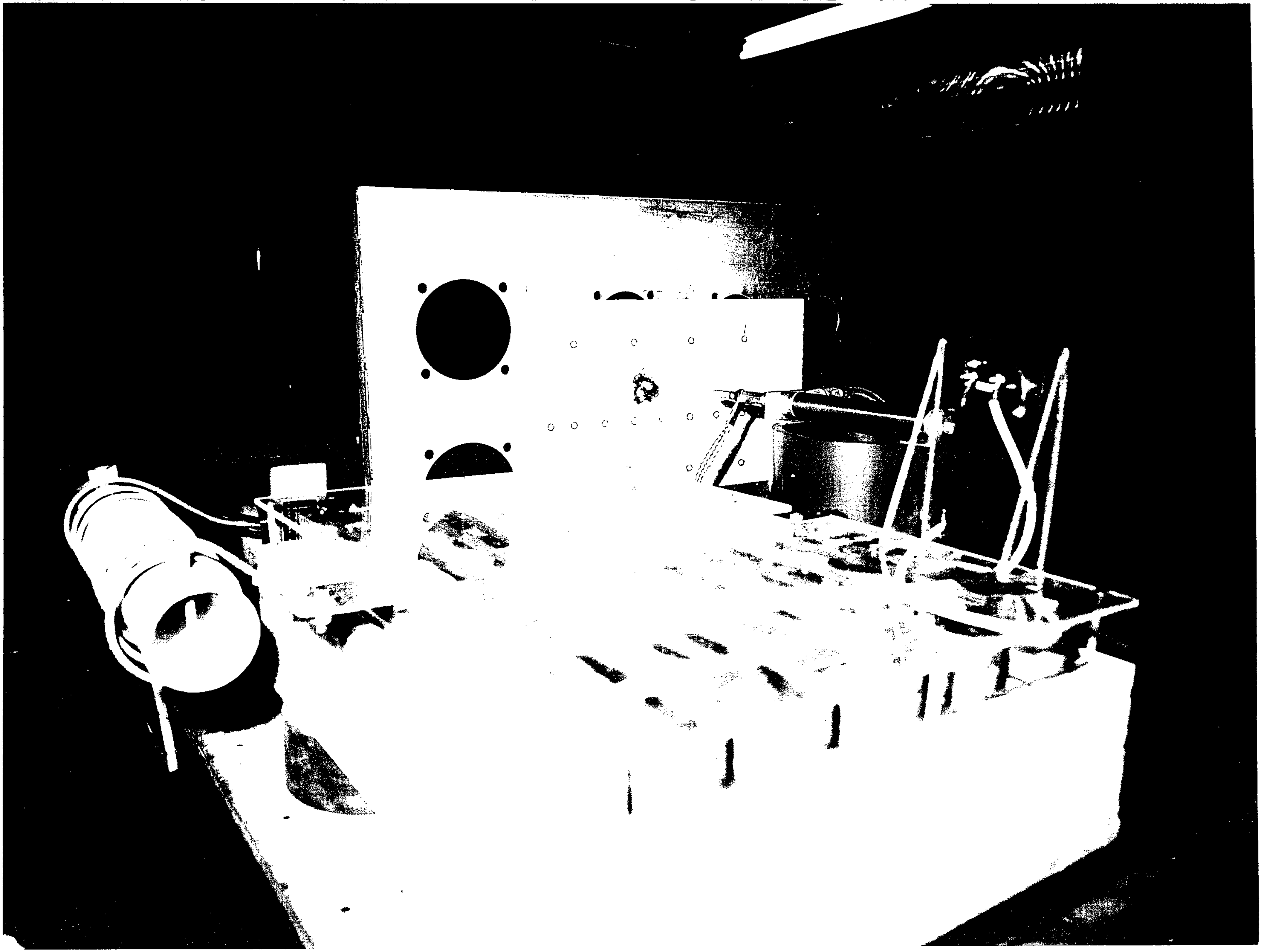


Figure 11. Test Setup for the Intermediate Current Lightning Test.

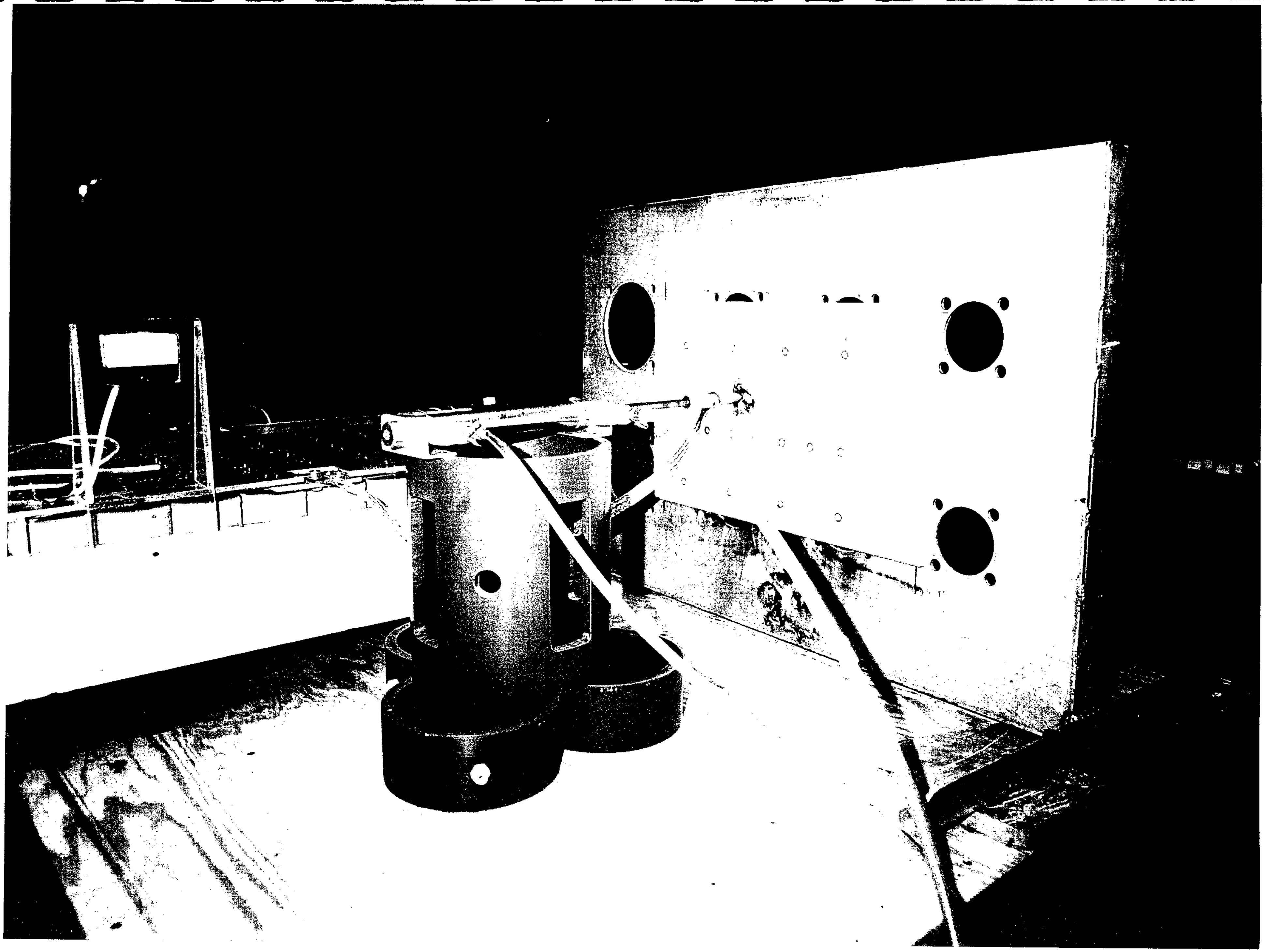


Figure 12. Test Setup for the Intermediate Current Lightning Test.

12. Repeat steps 1 through 9 for the restrike current (Component D) lightning generator. Figures 13 and 14 illustrate the test setup for the restrike current lightning test.

B. DEVIATIONS TO THE TEST PLAN

Four exceptions from the original test procedures (Appendix A) were taken during the direct strike lightning test of the MCC-1 TPS coated aluminum frustum and aft skirt panels. The first deviation was to conduct the high current (Component A) lightning test with the discharge probe positioned one inch from the panels rather than two inches. The second deviation consisted of utilizing only one each of the frustum and aft skirt calibration panels rather than all three of each. The third deviation was to subject frustum panel Q6#9 to two high current (Component A) attachments. The fourth deviation was to subject the two remaining frustum calibration panels to the high current (Component A) and the continuing current (Component C) direct strike lightning waveforms.

The first deviation was necessary to allow the high current lightning generator to maintain the specification level discharge to the test item. This deviation allowed the high current component to be tested similar to the TO2 test procedure of MIL-STD-1757. The TO2 test procedure of MIL-STD-1757 requires the gap between the discharge probe and the test item be 50 millimeters (mm) or approximately two inches for Component A and D tests to prevent the arc jet and blast pressure effects from influencing the test results.

The second deviation from the test procedures was to utilize only one frustum and one aft skirt calibration panel for calibration of the direct strike waveforms. It was not necessary to utilize all three of each of the frustum and the aft skirt calibration panels to calibrate the direct strike lightning waveforms. The same frustum and aft skirt calibration panels were utilized throughout the test in order to insure proper calibration with respect to the cumulative damage on the panels.

The third deviation from the test procedures was to subject frustum panel Q6#9 to two high current (Component A) attachments. This was necessary in order to record the correct high current direct strike lightning waveform measurement. On the first high current attachment to frustum panel Q6#9, the instrumentation system malfunctioned. A second high current attachment, at a different location, was necessary in order to correctly record the test waveform.

The fourth deviation from the test procedures was to subject the two remaining frustum calibration panels to the high current and continuing current direct strike lightning environment. Frustum calibration panel TTC5#16 was subjected to the high current (Component A) direct strike lightning environment with the discharge probe touching (no gap) the panel. This was done to compare the structural damage difference to the test panels which utilized a 1-inch gap between the discharge probe and the test panel. Frustum calibration panel TTC5#13 was subjected to the simultaneous high current (Component A) and continuing current (Component C) direct strike lightning environment with a separation distance of 1/4-inch between the discharge probe and the panel. This was done to compare the structural damage difference from the simultaneous application of the high current and continuing current direct strike lightning environment to the structural damage due to separate applications of these direct strike lightning environments.

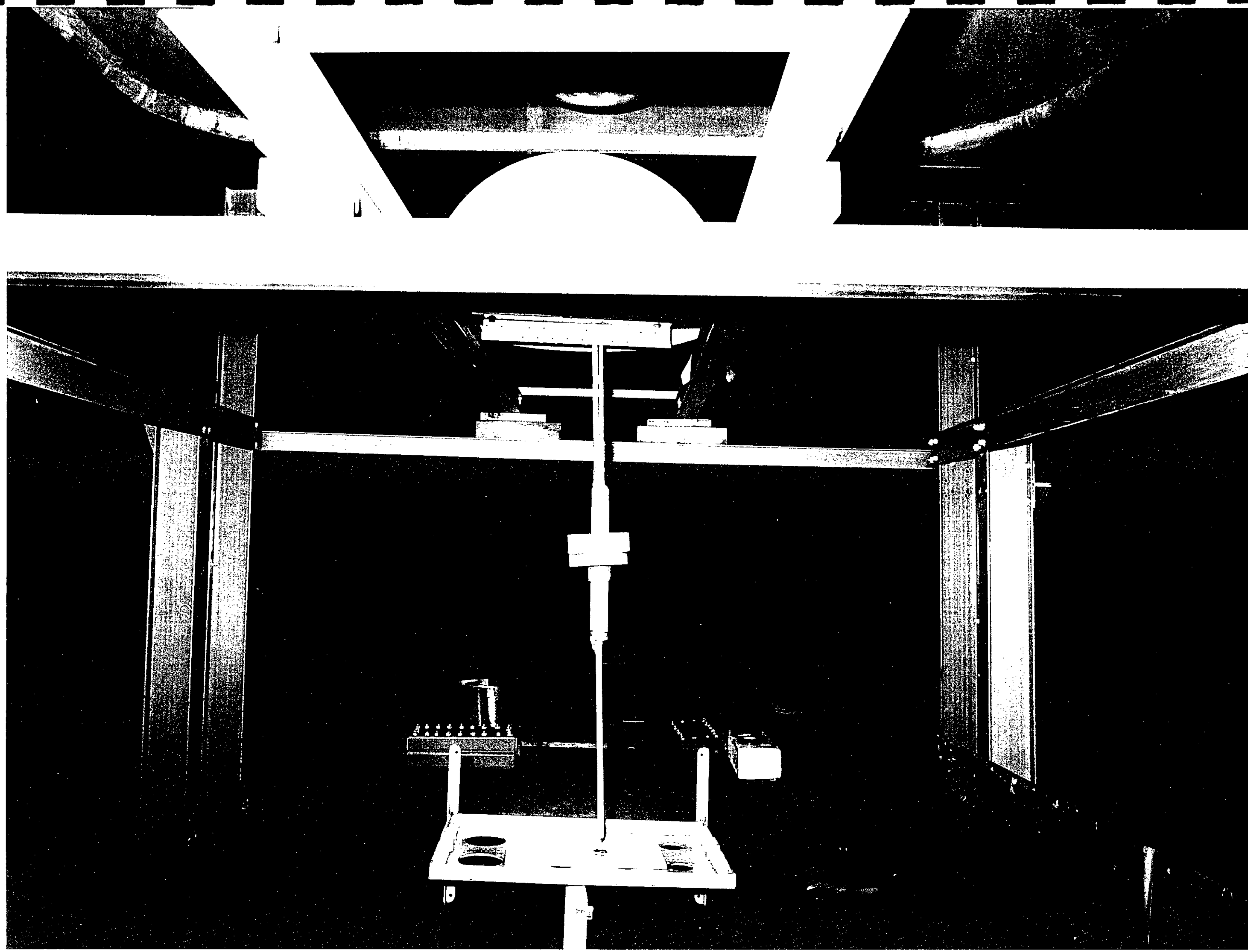


Figure 13. Test Setup for the Restrike Current Lightning Test.

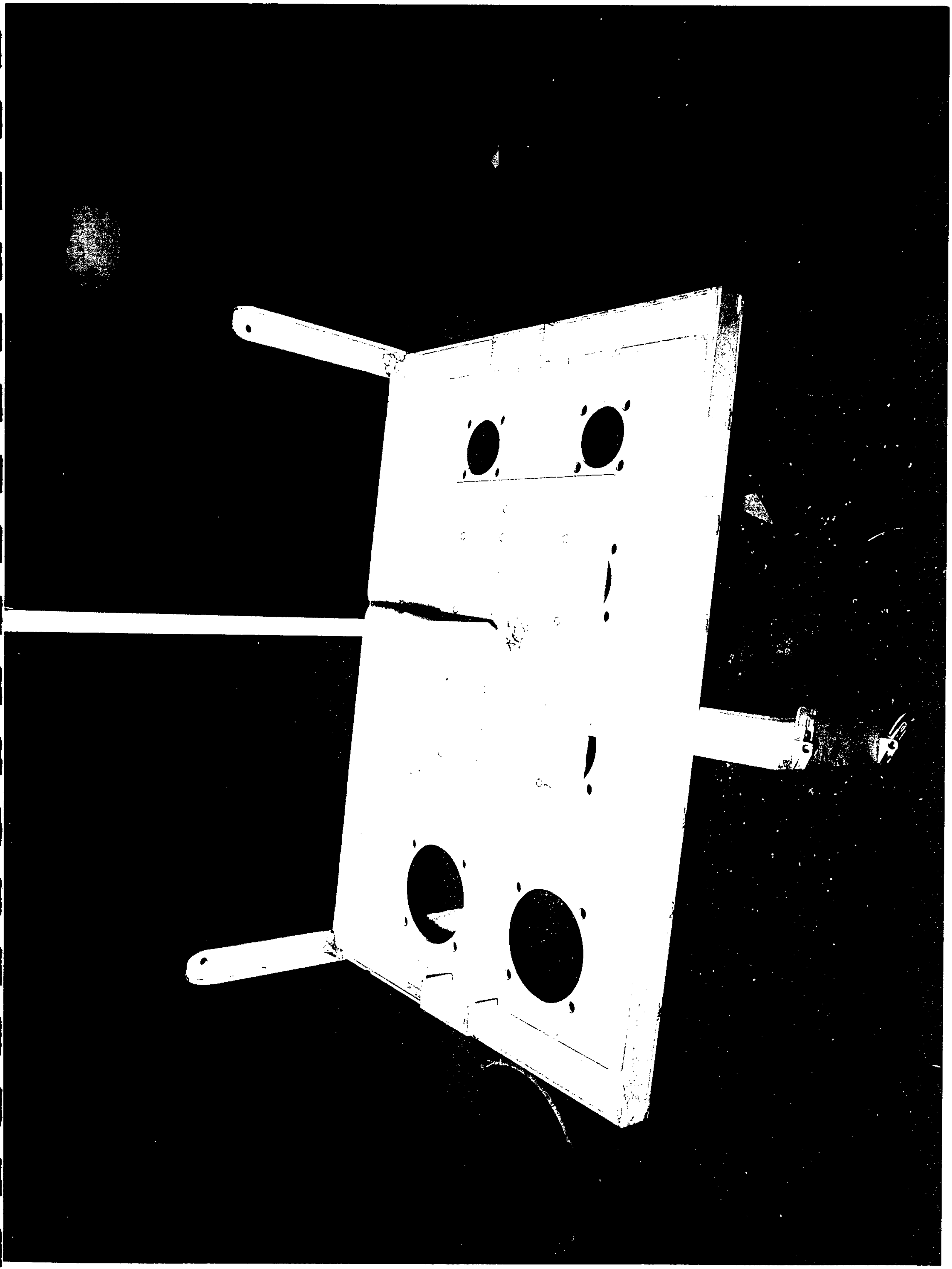


Figure 14. Test Setup for the Restrike Current Lightning Test.

VIII. RESULTS

All of the panels experienced loss of MCC-1 TPS coating at the point of discharge due to the application of the high current (Component A) direct strike lightning environment. The amount of MCC-1 TPS coating loss varied from panel to panel and seemed to depend on how well the material was bonded to the aluminum panel. For instance, comparison of the two separate attachments to frustum panel Q6#9 indicates different degrees of MCC-1 TPS coating loss. The first high current attachment resulted in a large area of loss of MCC-1 TPS coating while the second high current attachment resulted in significantly less loss of MCC-1 TPS coating. Additionally, the high current attachment to frustum panel Q13#2 resulted in the loss of a large circular section of MCC-1 TPS coating. The MCC-1 TPS coating was recovered in two approximately semi-circular solid pieces instead of being shattered into smaller pieces. Again, the degree of bonding of the MCC-1 TPS material to the aluminum panel appeared to be a determining factor in the amount of MCC-1 TPS coating loss. Figures B-1 through B-18 of Appendix B illustrate the damage on each panel due to the application of the Component A direct strike lightning waveform.

The application of the intermediate current (Component B) direct strike lightning environment resulted in a small melted (burn or blistered) spot on the aluminum panels approximately 1/4-inch in diameter. No additional loss of MCC-1 TPS coating was observed to occur due to the application of the intermediate current direct strike lightning environment. Figures B-19 through B-36 of Appendix B illustrate the cumulative damage on each panel due to the applications of the Component A and the Component B direct strike lightning waveforms.

The application of the continuing current (Component C) direct strike lightning environment resulted in a melted (burn or blistered) spot on the aluminum panels of up to approximately 3/4-inch in diameter. No additional loss of MCC-1 TPS coating was observed to occur due to the application of the intermediate current direct strike lightning environment. Figures B-37 through B-54 of Appendix B illustrate the cumulative damage on each panel due to the applications of the Component A, the Component B, and the Component C direct strike lightning waveforms.

The application of the restrike current (Component D) direct strike lightning environment resulted in slight blackening of the MCC-1 TPS coating around the area of the discharge point. No additional loss of MCC-1 TPS coating was observed to occur due to the application of the intermediate current direct strike lightning environment. Figures B-55 through B-72 of Appendix B illustrate the cumulative damage on each panel due to the applications of the Component A, the Component B, the Component C, and the Component D direct strike lightning waveforms.

The application of the high current (Component A) direct strike lightning environment to frustum calibration panel TTC5#16 with the discharge probe touching the panel did not appear to result in any significant difference of loss of MCC-1 TPS coating than to the test panels which utilized a 1-inch gap between the discharge probe and the test panels. Figures B-73 through B-75 of Appendix B illustrate the damage on the panel due to the application of the Component A direct strike lightning waveform.

The simultaneous application of the high current (Component A) and the continuing current (Component C) lightning environment to frustum calibration panel TTC5#13 resulted in the loss of MCC-1 TPS coating and melting (burn or blistering) similar to the test panels. The significant difference was that the MCC-1 TPS coating ignited and burned as a result of the simultaneous application of the high current and continuing current direct strike lightning environment. Figures B-76 through B-78 of Appendix B illustrate the damage on the panel due to the simultaneous application of the Component A and the Component C direct strike lightning waveforms.

TABLE 1. DIRECT STRIKE LIGHTNING TEST MEASUREMENTS

Test No.	Panel Type	File No.	Panel No.	Comp. A		Comp. B		Comp. C		Comp. D		Comments
				Peak Current (kA)	Action integral (A^2 sec)	Peak Current (A)	Charge (C)	Peak Current (A)	Charge (C)	Peak Current (kA)	Action integral (A^2 sec)	
1	Frustum	SRBCALA1		201	$1.82x10^6$	x	x	x	x	x	x	Calibration; See Fig. C-1
2	Aft Skirt	SRBCALA2		196	$1.80x10^6$	x	x	x	x	x	x	Calibration; See Fig. C-2
3	Frustum	SS1Q6#9A	Q6#9	x	x	x	x	x	x	x	x	Instr Error; See Fig. B-1, B-2 and C-3
4	Frustum	SS2Q6#9A	Q6#9	206	$194x10^6$	x	x	x	x	x	x	See Fig. B-3, B-4 and C-4
5	Frustum	S1Q6#10A	Q6#10	207	$1.95x10^6$	x	x	x	x	x	x	See Fig. B-5, B-6 and C-5
6	Frustum	S1Q13#2A	Q13#2	206	$1.92x10^6$	x	x	x	x	x	x	See Fig. B-7 thru B-12 and C-6
7	Aft Skirt	S1Q11#6A	Q11#6	207	$1.97x10^6$	x	x	x	x	x	x	See Fig. B-13, B-14 and C-7
8	Aft Skirt	S1Q11#8A	Q11#8	204	$1.88x10^6$	x	x	x	x	x	x	See Fig. B-15, B-16 and C-8
9	Aft Skirt	S1Q11#9A	Q11#9	202	$1.84x10^6$	x	x	x	x	x	x	See Fig. B-17, B-18 and C-9
10	Frustum	SRBCALB1		x	x	5476	10.0	x	x	x	x	Calibration; See Fig. C-10
11	Aft Skirt	SRBCALB2		x	x	5123	9.3	x	x	x	x	Calibration; See Fig. C-11
12	Frustum	SS1Q6#9B	Q6#9	x	x	5679	10.3	x	x	x	x	See Fig. B-19 thru B-21 and C-12
13	Frustum	S1Q6#10B	Q6#10	x	x	5716	10.3	x	x	x	x	See Fig. B-22 thru B-24 and C-13
14	Frustum	S1Q13#2B	Q13#2	x	x	5679	10.3	x	x	x	x	See Fig. B-25 thru B-27 and C-14
15	Aft Skirt	S1Q11#6B	Q11#6	x	x	5679	10.3	x	x	x	x	See Fig. B-28 thru B-30 and C-15
16	Aft Skirt	S1Q11#8B	Q11#8	x	x	5603	10.1	x	x	x	x	See Fig. B-31 thru B-33 and C-16
17	Aft Skirt	S1Q11#9B	Q11#9	x	x	5565	10.1	x	x	x	x	See Fig. B-34 thru B-36 and C17
18	Frustum	SRBCALC1		x	x	x	x	521	200	x	x	Calibration; See Fig. C-18
19	Frustum	SS1Q6#9C	Q6#9	x	x	x	x	534	200	x	x	Probe Contact Too Good; See Fig. C-19
20	Frustum	SS2Q6#9C	Q6#9	x	x	x	x	534	203	x	x	See Fig. B-37 thru B-39 and C-20
21	Frustum	S1Q6#10C	Q6#10	x	x	x	x	534	204	x	x	See Fig. B-40 thru B-42 and C-21
22	Frustum	S1Q13#2C	Q13#2	x	x	x	x	547	204	x	x	See Fig. B-43 thru B-45 and C-22
23	Aft Skirt	S1Q11#6C	Q11#6	x	x	x	x	534	207	x	x	See Fig. B-46 thru B-48 and C-23
24	Aft Skirt	S1Q11#8C	Q11#8	x	x	x	x	534	199	x	x	See Fig. B-49 thru B-51 and C-24
25	Aft Skirt	S2Q11#9C	Q11#9	x	x	x	x	547	203	x	x	See Fig. B-52 thru B-54 and C-25
26	Frustum	SRBCALD1		x	x	x	x	x	x	92	$0.39x10^6$	Calibration; See Fig. C-26
27	Aft Skirt	SRBCALD2		x	x	x	x	x	x	91	$0.35x10^6$	Calibration; See Fig. C-27
28	Frustum	SS1Q6#9D	Q6#9	x	x	x	x	x	x	93	$0.39x10^6$	See Fig. B-55 thru B-57 and C-28
29	Frustum	S1Q6#10D	Q6#10	x	x	x	x	x	x	92	$0.42x10^6$	See Fig. B-58 thru B-60 and C-29
30	Frustum	S1Q13#2D	Q13#2	x	x	x	x	x	x	94	$0.40x10^6$	See Fig. B-61 thru B-63 and C-30
31	Aft Skirt	S1Q11#6D	Q11#6	x	x	x	x	x	x	91	$0.35x10^6$	See Fig. B-64 thru B-66 and C-31
32	Aft Skirt	S1Q11#8D	Q11#8	x	x	x	x	x	x	94	$0.39x10^6$	See Fig. B-67 thru B-69 and C-32
33	Aft Skirt	S1Q11#9D	Q11#9	x	x	x	x	x	x	92	$0.43x10^6$	See Fig. B-70 thru B-72 and C-33
34	Frustum	TTC5#16A	TTC5#16	209	$1.88x10^6$	x	x	x	x	x	x	No Gap; See Fig. B-73 thru B-75 and C-34
35	Frustum	TC5#13AC	TTC5#13	209	$1.99x10^6$	471	167	x	x	x	x	Ignited; See Fig. B-76 thru B-78 , C-35 and C36

APPENDIX A

DIRECT STRIKE LIGHTNING EFFECTS TEST PROCEDURES FOR THE MCC-1
TPS COATED ALUMINUM PANELS

DIRECT STRIKE LIGHTNING EFFECTS TEST PROCEDURES FOR THE MCC-1 TPS COATED ALUMINUM PANELS

6 January 1995

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I. INTRODUCTION

As part of the SRB TPS replacement program qualification test effort, the MCC-1 is required to be subjected to lightning testing as specified in NSTS 07636 Rev. G to verify that the design is sufficient to ensure the protection of the space shuttle from the direct and indirect effects of lightning. The particular scope of this test effort is to determine the structural direct effects of lightning to the frustum and aft skirt panels. The frustum panel has dimensions of 12 x 20 inch with an aluminum thickness of 0.125 inches and a TPS thickness of 0.190 inches. The aft skirt panel has an aluminum thickness of 0.25 inches and a TPS thickness of 0.460 inches.

II. TEST OBJECTIVE

The objective of this lightning effects test is to determine and assess the structural direct effects of lightning to the frustum and aft skirt panels of the space shuttle. This effort will not assess the indirect effects of lightning from a direct strike, nor near strike, lightning event on the frustum or aft skirt panels.

III. TEST ENVIRONMENT

The environments required for this test effort are for Zone 1B type lightning strikes as specified in MIL-STD-1757A. Since the objective of this test effort is to determine the structural direct effects of lightning to the frustum and aft skirt panels of the space shuttle, test method T02 of MIL-STD-1757A will be utilized to test lightning current waveform Components A, B, C, and D. The requirements for these lightning current waveform components are defined in Figure 1.

IV. EVALUATION CRITERIA

The criteria for this test effort is to determine that the MCC-1 TPS coated aluminum frustum and aft skirt panels are subjected to the specified lightning current environment.

V. TEST RESPONSIBILITY

A. Redstone Technical Test Center

The RTTC is responsible for planning and conducting all tests, coordinating and scheduling test facilities, establishing and applying security and safety procedures, providing system instrumentation and test fixtures, modifying test hardware as required, collecting and analyzing test data, and providing a final report or report letter.

B. United Technologies Corporation/United States Booster Incorporated

United Technologies Corporation/United States Booster Incorporated (UTC/USBI) is responsible for providing overall coordination of the test program, including, but not limited to, supplying technical assistance, providing funds, identifying and providing all test hardware, and support hardware, and for the evaluation of the frustum and aft skirt panels with respect to space shuttle flight safety and crew hazard.

VI. FACILITIES AND EQUIPMENT REQUIREMENTS

This section describes the test hardware, facility and instrumentation necessary to conduct the structural direct effects lightning test of the MCC-1 TPS coated aluminum frustum and aft skirt panels.

A. TEST HARDWARE

The test hardware will be provided by UTC/USBI and will consist of six frustum panels and six aft skirt panels coated with MCC-1 TPS (Figure 2). Three of the frustum panels, as well as three of the aft skirt panels, will provided for calibration purposes.

B. FACILITY

This section describes the various components comprising the simulated direct strike lightning equipment of the Hazardous Lightning (HELS) Test Facility.

1. HIGH CURRENT CAPACITOR BANK

The high current (Component A) capacitor bank consists of 480 capacitors, each rated at 60 kV and 1.875 MF, configured as a two-stage Marx bank with a total capacitance of 56.25 MF and an output voltage of 220 kV. A 2.25 MF, 300 kV peaking capacitor circuit is utilized in conjunction with the high current capacitor bank to increase the current rate-of-rise time to 6.5 msec. The high current capacitor bank can generate a 200 kA ± 10% peak current simulated Component A direct strike lightning waveform with an action integral of 2.0×10^6 A^2sec ± 20% (Figure 1b).

2. INTERMEDIATE CURRENT CAPACITOR BANK

The Intermediate Current (Component B) Capacitor Bank consists of 5 layers of electrolytic capacitors connected in series. Each layer contains 8, 450 volt, 3000 MF capacitors in parallel. The total calculated capacitance is 4800 MF. The charge voltage is 2100 V. The intermediate current capacitor bank can generate a 2000 A 10% simulated direct strike Component B waveform with a peak current of approximately 5800 A and 10 Coulombs (C) of charge transfer (Figure 1b).

3. CONTINUING CURRENT CAPACITOR BANK

The Continuing Current (Component C) Capacitor Bank consists of two layers of electrolytic capacitors connected in series. Each layer contains 196, 450 volt, 3000 MF capacitors in parallel. The total measured capacitance is 0.37 F when charged to a nominal value of 750 V. The continuing current capacitor bank can generate a simulated Component C waveform with 200 C ± 20% of charge transfer (Figure 1c).

4. HIGH VOLTAGE RESTRIKE MARX CAPACITOR BANK

The High Voltage Restrike Marx (Component D) Capacitor Bank is an 18 stage Marx bank with a total capacitance of 0.9375 MF. Each stage, consisting of nine 60 kV, 1.875 MF capacitors in parallel, is nonnally charged to 42 kV to provide a total output voltage of 756 kV. Energy from the Marx bank is delivered to the peaking capacitor/spark gap assembly via an one-inch insulated conductor. The peaking capacitor bank has a total capacitance of 0.027 MF and a maximum voltage capability of 2.2 megavolts. The peaking capacitor bank consists of two parallel stacks of Maxwell

capacitors. Each stack contains twenty-two 0.3 mF, 100 kV capacitors in series. The high voltage restrike Marx capacitor bank can generate a 100 kA ± 10% peak current simulated Component D waveform with an average current rate-of-rise of 1.0×10^{11} A/sec and a maximum current rate-of-rise of 1.4×10^{11} A/sec ± 20% (Figure 1c).

C. TEST INSTRUMENTATION

The objective of the test effort was to subject the frustum and aft skirt panels to a simulated direct strike lightning test to determine the direct effects only; therefore, only the injection current waveforms are necessary to monitor to insure compliance with the simulated direct strike lightning environment criteria. Instrumentation of the frustum or aft skirt panels were not necessary.

1. HIGH CURRENT INSTRUMENTATION

A Pearson Model 1080 Current Probe is utilized as the sensor for the high current waveform measurement. The current probe is installed on the center conductor of the High Current/Continuing Current Discharge Probe. The high current waveform measurement is telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal is recorded on a Hewlett-Packard Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

2. INTERMEDIATE CURRENT INSTRUMENTATION

A ??? Ohm series resistor is utilized as the sensor for the intermediate current waveform measurement. The resistor is installed in-line with the intermediate current transmission line. The intermediate current waveform measurement is telemetered via a Meret Model MDL281-4-C Fiber Optic System. The signal is recorded on an HP 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

3. CONTINUING CURRENT INSTRUMENTATION

A 0.12 Ohm series resistor is utilized as the sensor for the continuing current waveform measurement. The resistor is installed in-line with the continuing current transmission line. The continuing current waveform measurement is telemetered via a Meret Model MDL281-4-C Fiber Optic System. The signal is recorded on an HP 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

4. HIGH VOLTAGE RESTRIKE INSTRUMENTATION

A Pearson Model 1080 Current Probe is utilized as the sensor for the high voltage restrike waveform measurement. The current probe is installed on the center conductor of the High Voltage Restrike Down Conductor. The high voltage restrike waveform measurement is telemetered via a Nanofast Model OP-300 Fiber Optic System. The signal is recorded on an HP Model 54510 A/D Digital Oscilloscope and reduced on an IBM compatible PC.

VII. TEST PROCEDURE

The frustum and aft skirt panels will be subjected to the simulated direct strike lightning environment described in Figure 1 to determine the structural direct effects of lightning on the frustum and aft skirt panels. The direct effects lightning test will be divided into four phases: high current test ; intermediate current test; continuing current test; and high voltage restrike test.

A. GENERAL TEST PROCEDURES

Operating procedures for the HELS facility are described in the "Hazardous Test Procedures For High Energy Lightning Simulator (HELS)", AMSMI-RD-S-H-6, May 1987, and the associated Addendum dated 26 August 1988. The following is a general test procedure that will be followed for each test sequence:

1. Perform pretest calibration of the simulated direct strike lightning generators on the frustum and aft skirt calibration panels.

2. Bolt the frustum panel onto the ground return plate of the test fixture.

3. Install instrumentation and set up the high current (Component A) lightning generator and associated test equipment.

4. Charge high current lightning generator.

5. Initiate video recording sequence.

6. Discharge to the center portion of the frustum panel.

7. Record test data.

8. Repeat steps 2 through 7 for the remaining five frustum panels.

9. Repeat steps 2 through 7 for the six aft skirt panels.

10. Repeat steps 2 through 9 for the intermediate current (Component B) lightning generator.

11. Repeat steps 2 through 9 for the continuing current (Component C) lightning generator.

12. Repeat steps 2 through 9 for the restrike current (Component D) lightning generator.

VIII. DOCUMENTATION

General documentation for the structural direct effects lightning test includes the following, but is not limited to:

* Serial numbers of test hardware (if applicable) and calibration information

* Non-standard modification of test hardware

* Hardware configuration

* Non-test related problems/failures

* Pre-test, post-test, etc. inspection results

* Daily log for test activities

* Direct strike lightning generator/power supply used, including ancillary equipment

* Four sets of color 8 x 10 inch still photographs of test setup

* Four sets of color 8 x 10 inch still photographs of each panel before and after test

* Two copies of video photography of the lightning strike test events.

Detailed documentation for each test run shall include the following, but is not limited to:

* Test run number

* Test criteria

* Direct strike lightning current waveforms and test parameters

* Results of visual inspection of the frustum and aft skirt panels.

APPENDIX B

PHOTOGRAPHS

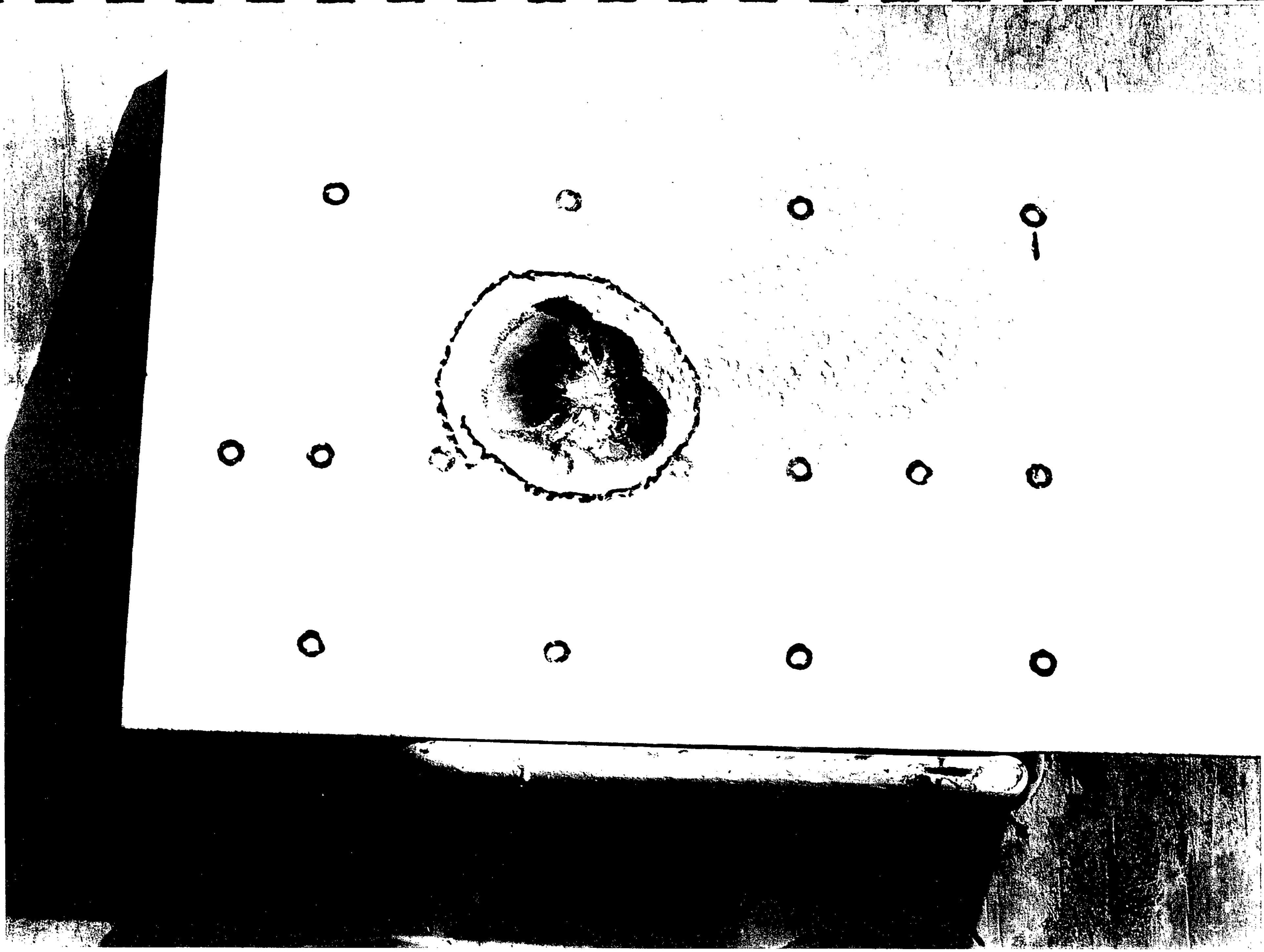


Figure B-1. Resultant Damage Due to Component A to Panel Q-6#9, Front View.

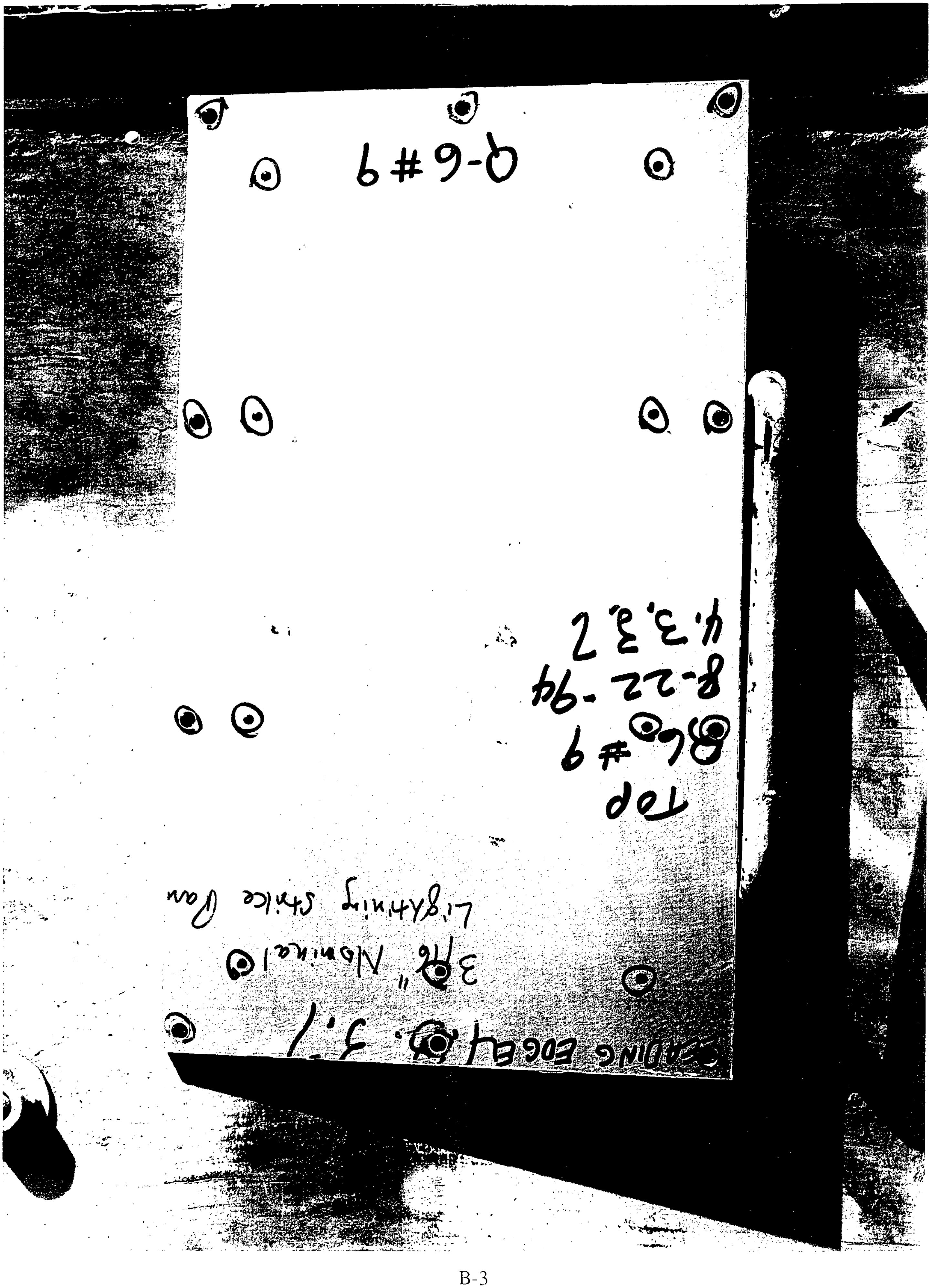


Figure B-2. Resultant Damage Due to Component A to Panel Q-6#9, Back View.

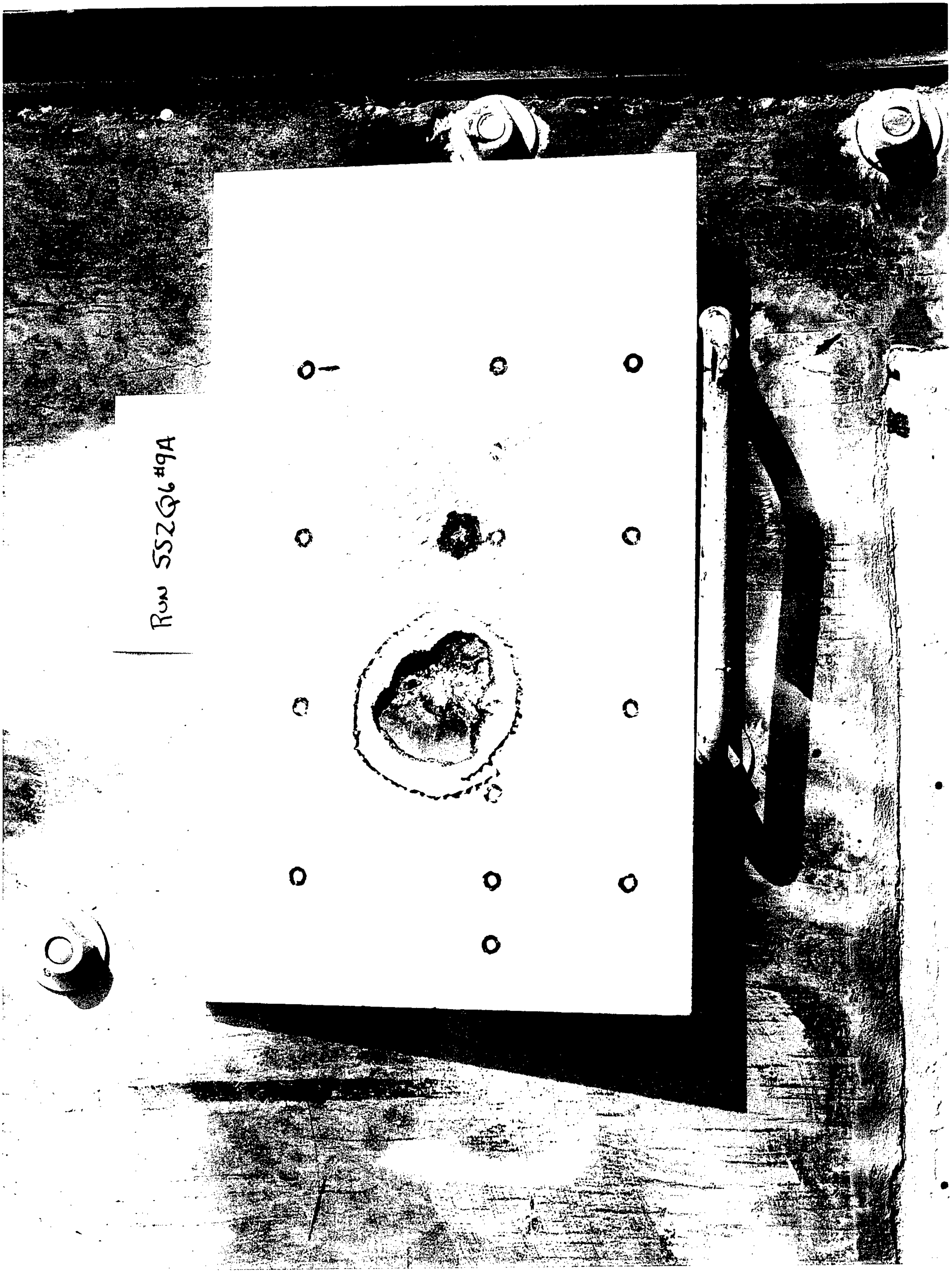


Figure B-3. Resultant Damage Due to Component A to Panel Q-6#9, Front View (2nd Test).

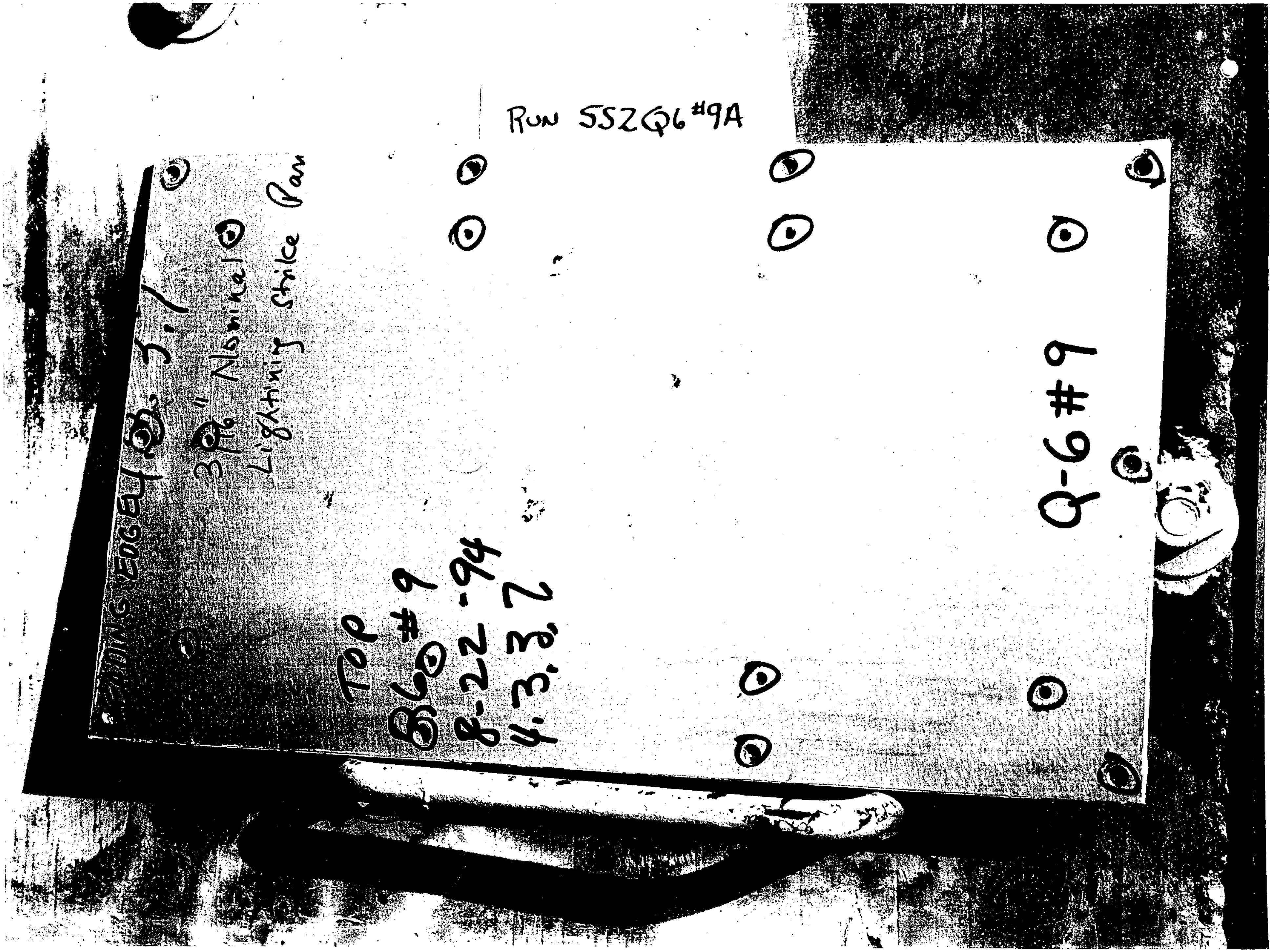


Figure B-4. Resultant Damage Due to Component A to Panel Q-6#9, Back View (2nd Test).

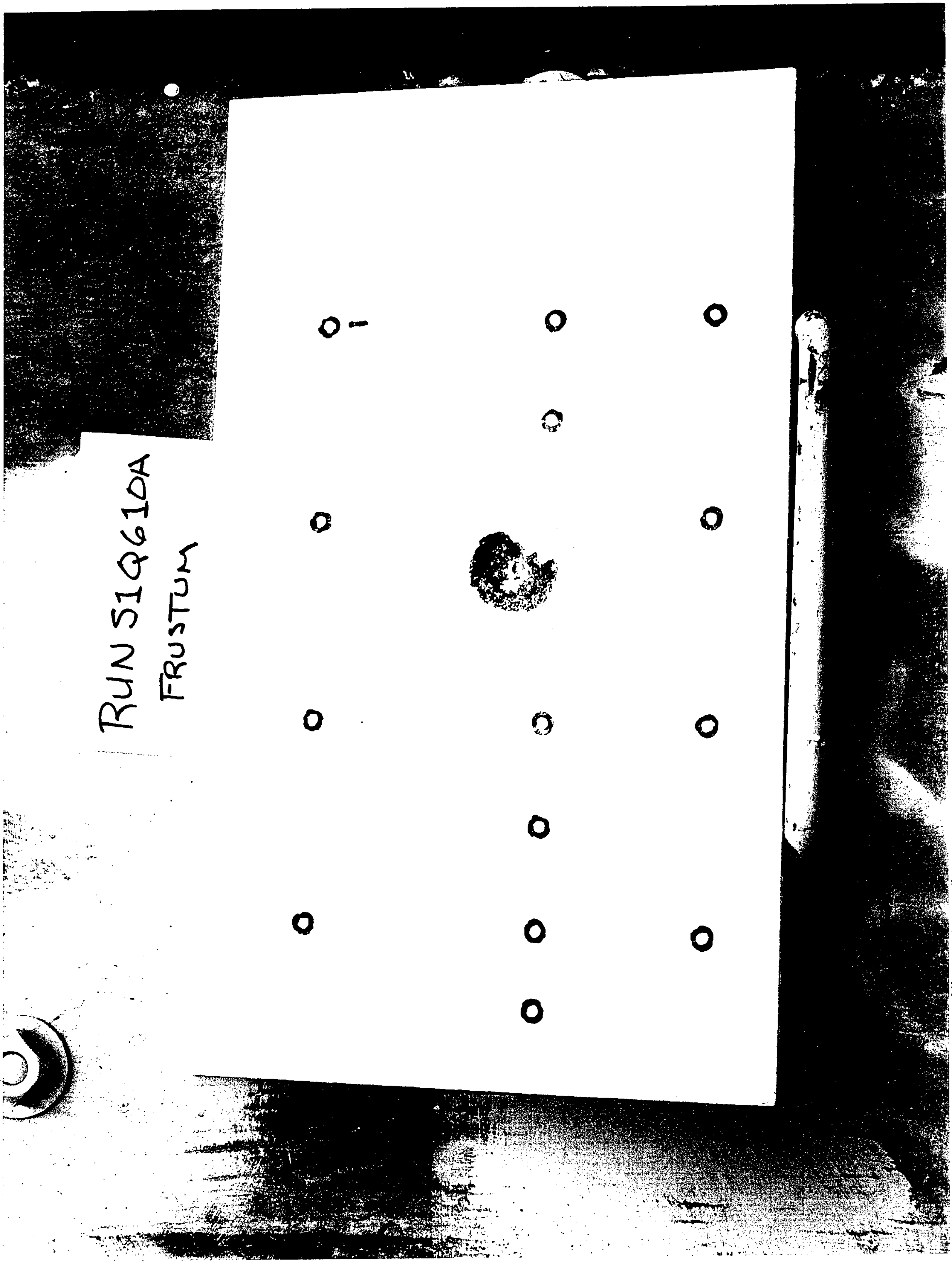


Figure B-5. Resultant Damage Due to Component A to Panel Q-6#10, Front View.

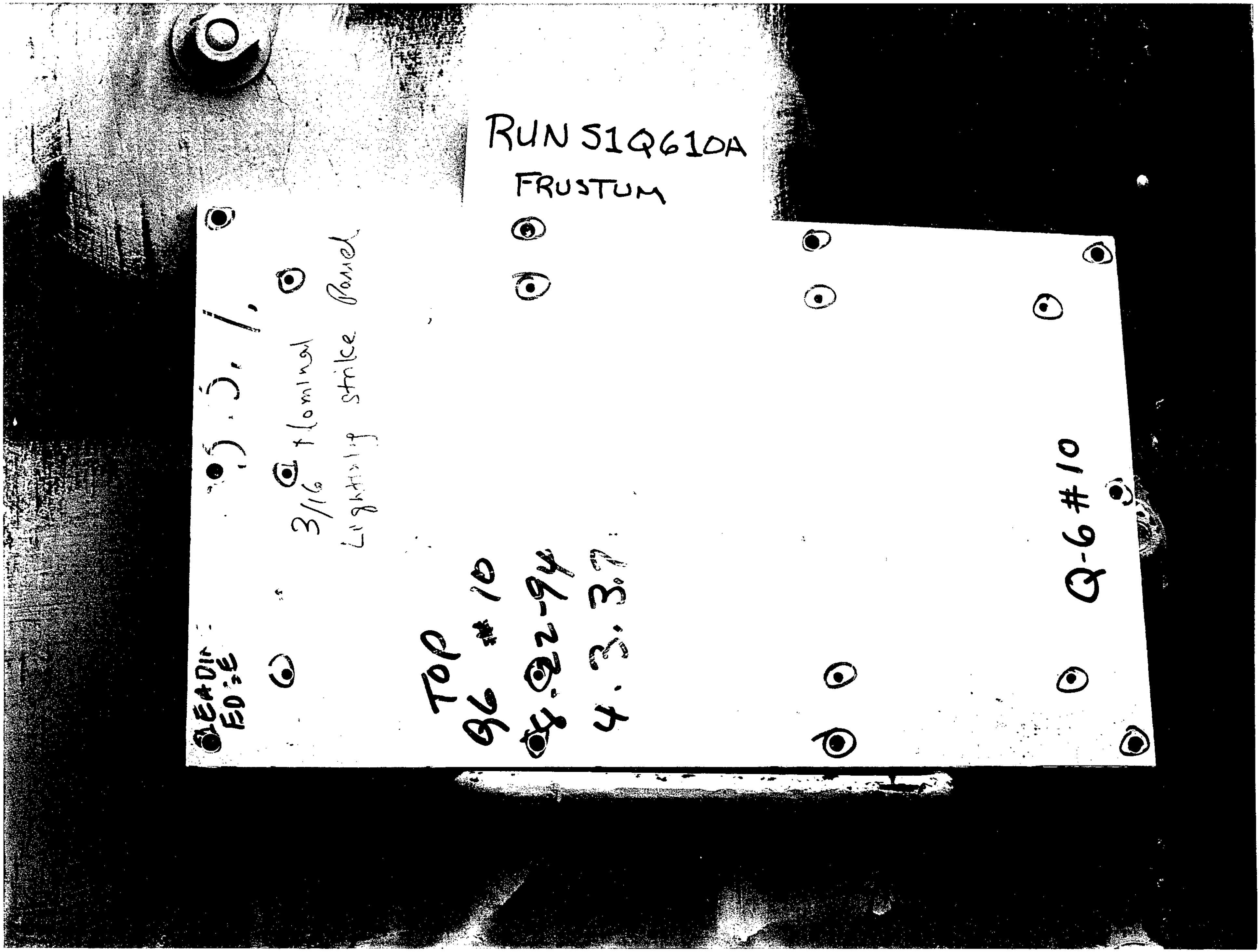


Figure B-6. Resultant Damage Due to Component A to Panel Q-6#10, Back View.

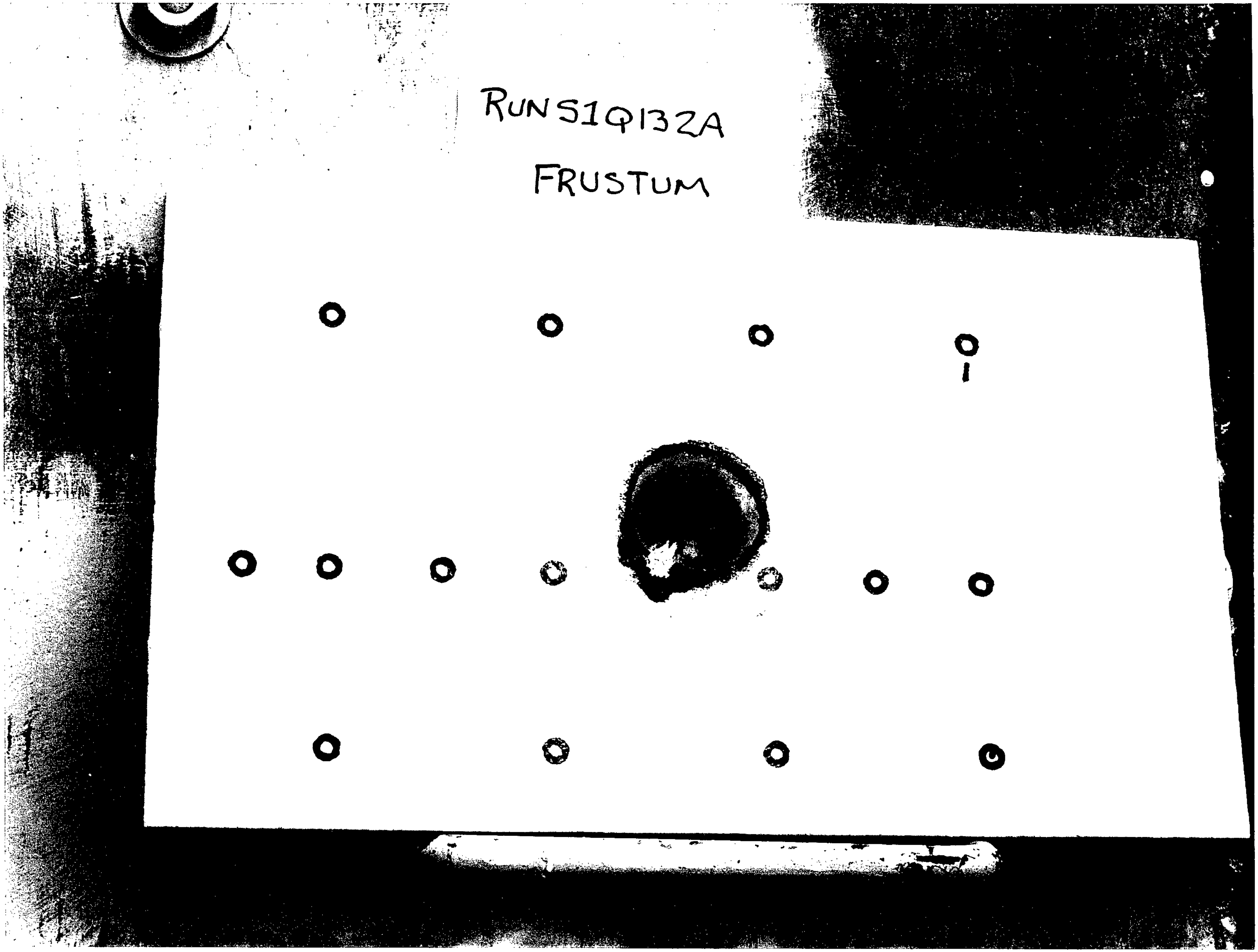


Figure B-7. Resultant Damage Due to Component A to Panel Q-13#2, Front View.

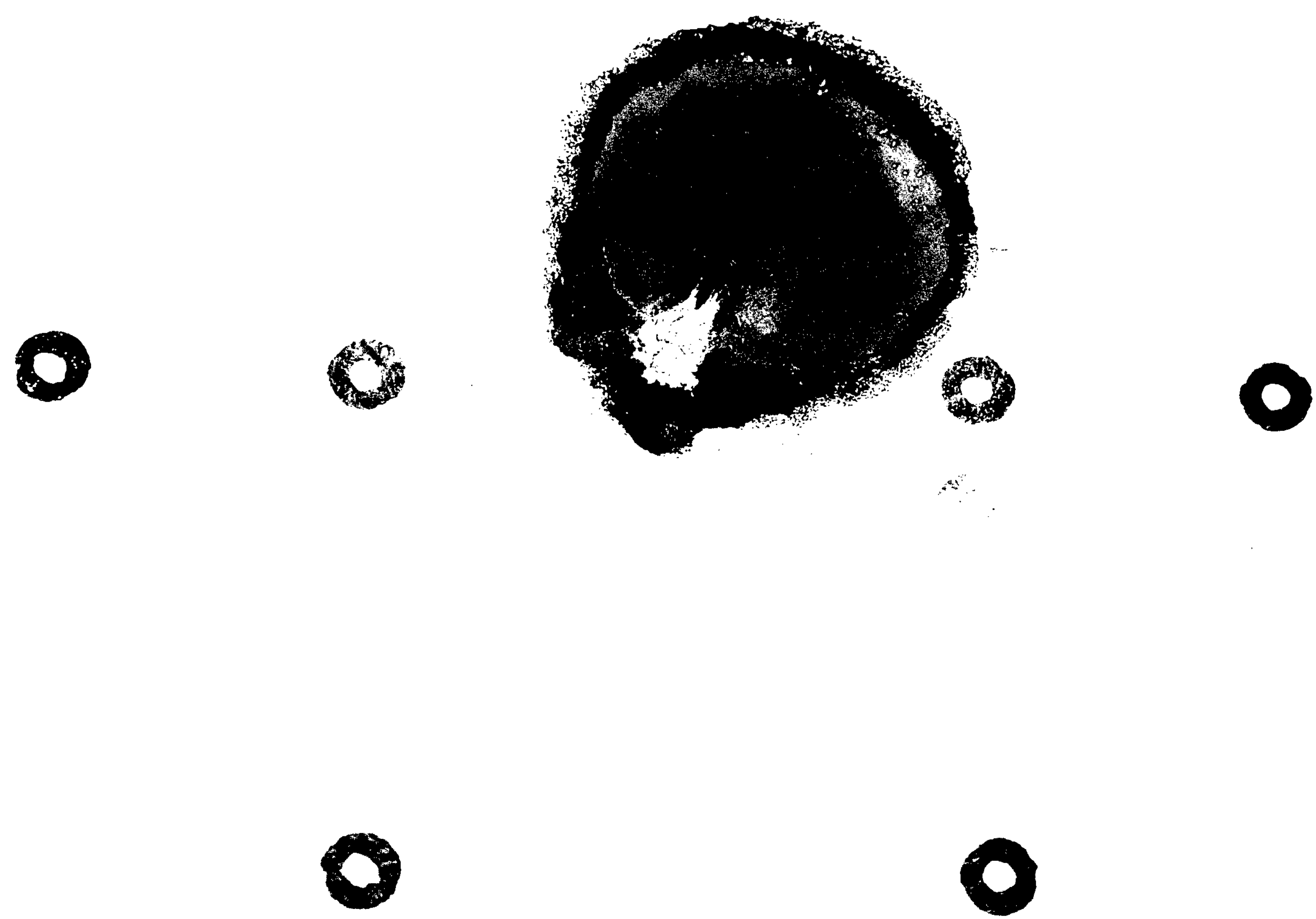


Figure B-8. Resultant Damage Due to Component A to Panel Q-13#2, Close Up View.

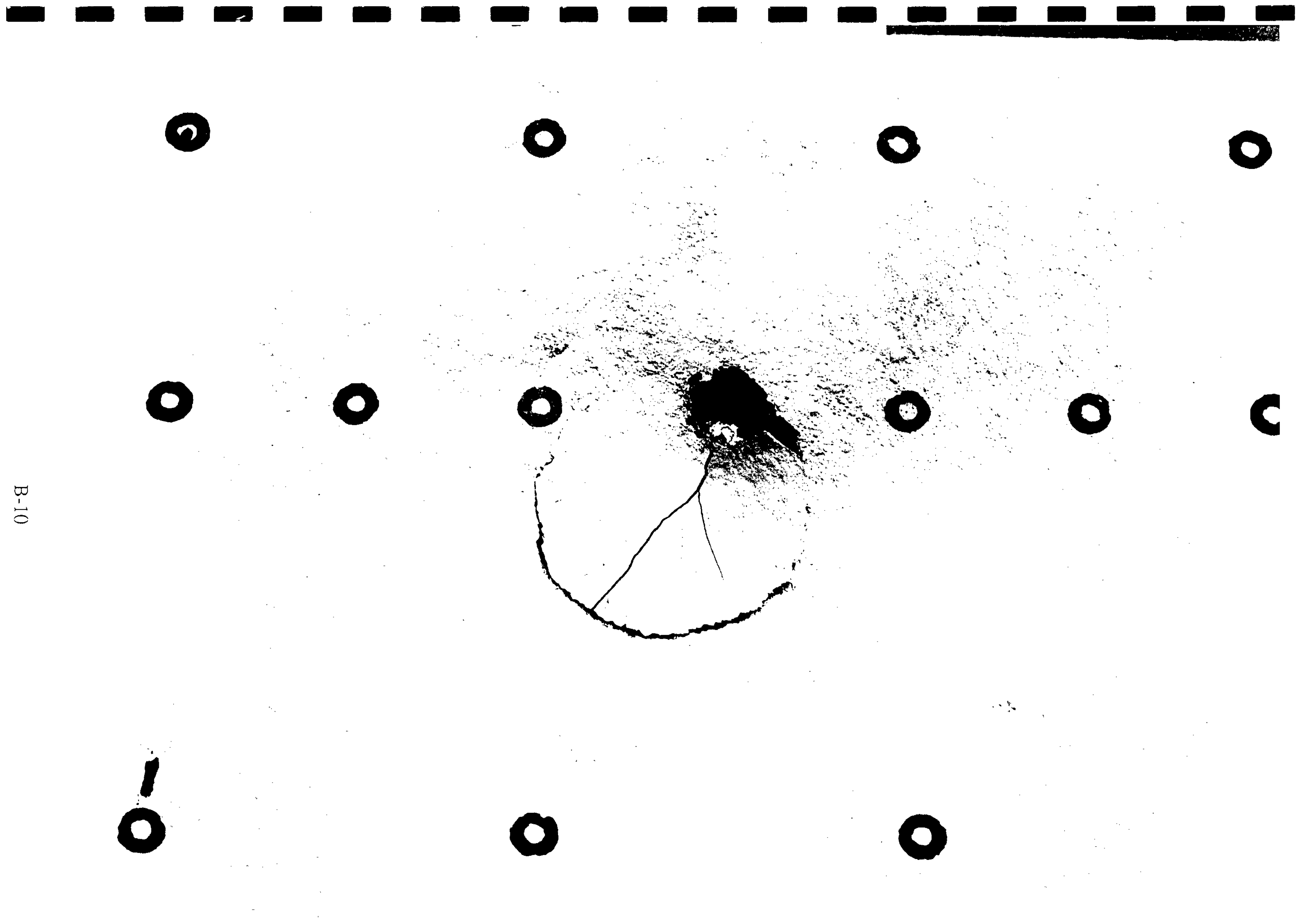


Figure B-9. Resultant Damage Due to Component A to Panel Q-13#2, Pieces Replaced.

Figure B-10. Resultant Damage Due to Component A to Panel Q-13#2, Back View with Pieces.

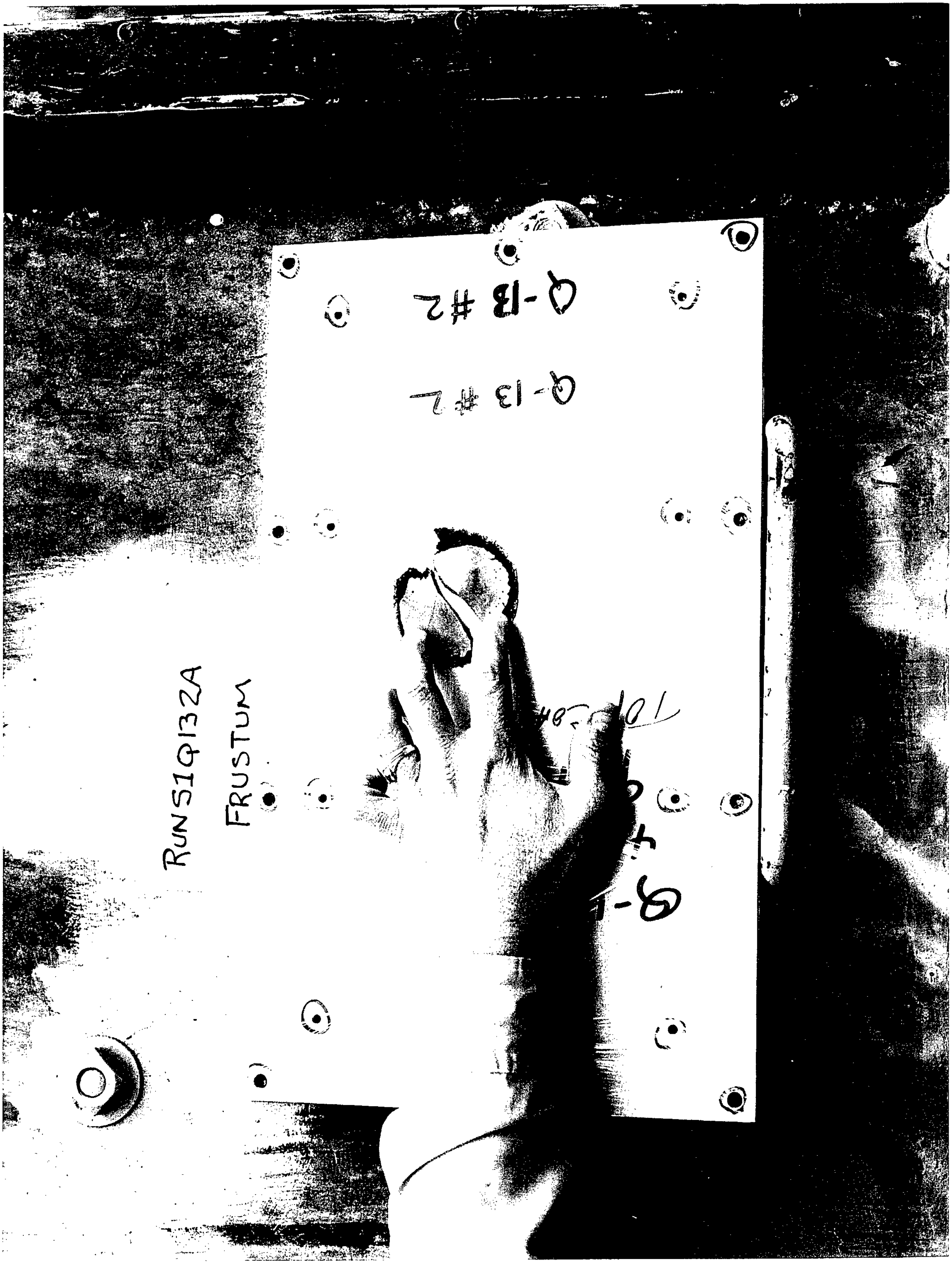


Figure B-11. Resultant Damage Due to Component A to Panel Q-13#2, Back View with Pieces.

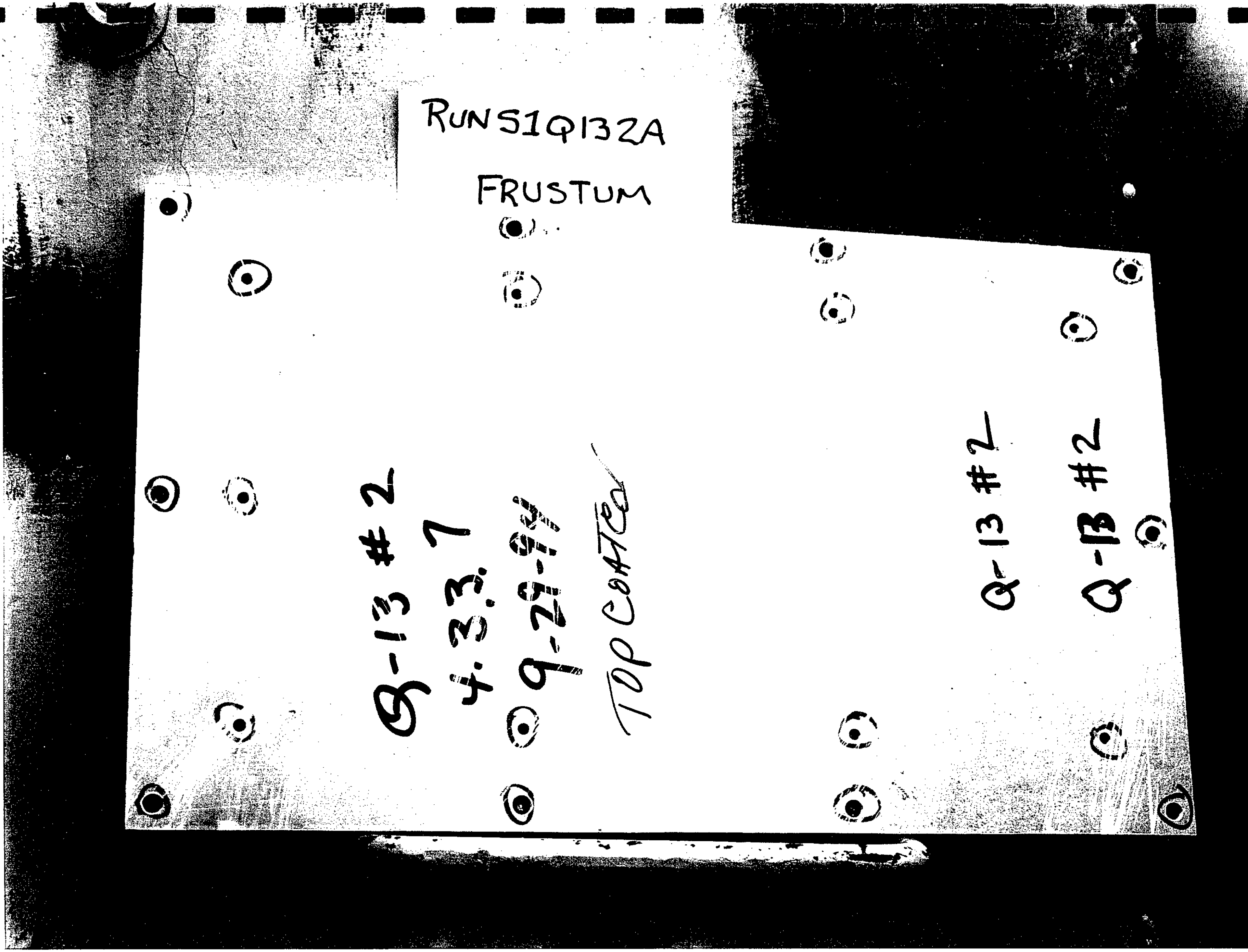


Figure B-12. Resultant Damage Due to Component A to Panel Q-13#2, Back View.

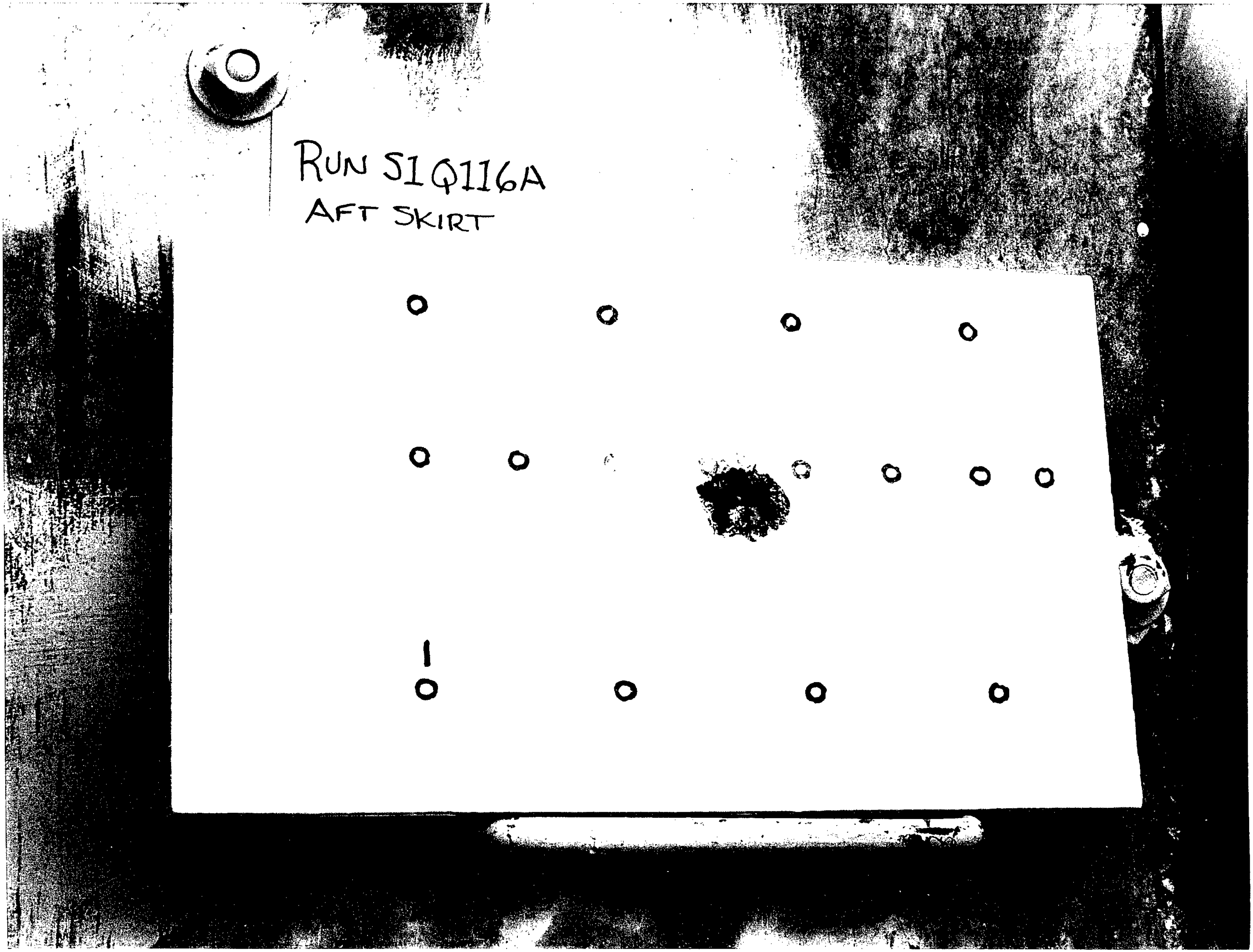


Figure B-13. Resultant Damage Due to Component A to Panel Q-11#6, Front View.

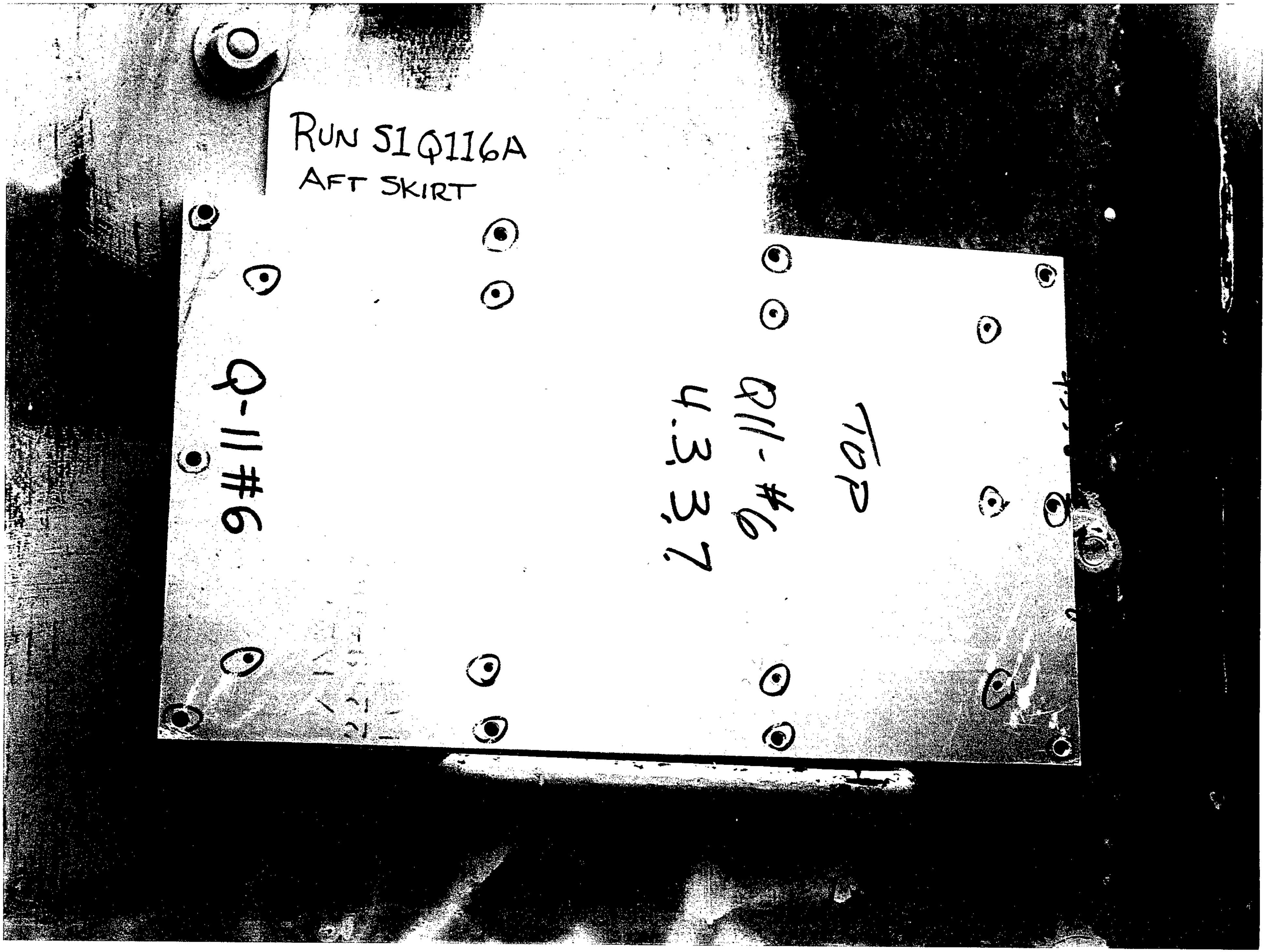


Figure B-14. Resultant Damage Due to Component A to Panel Q-11#6, Back View.

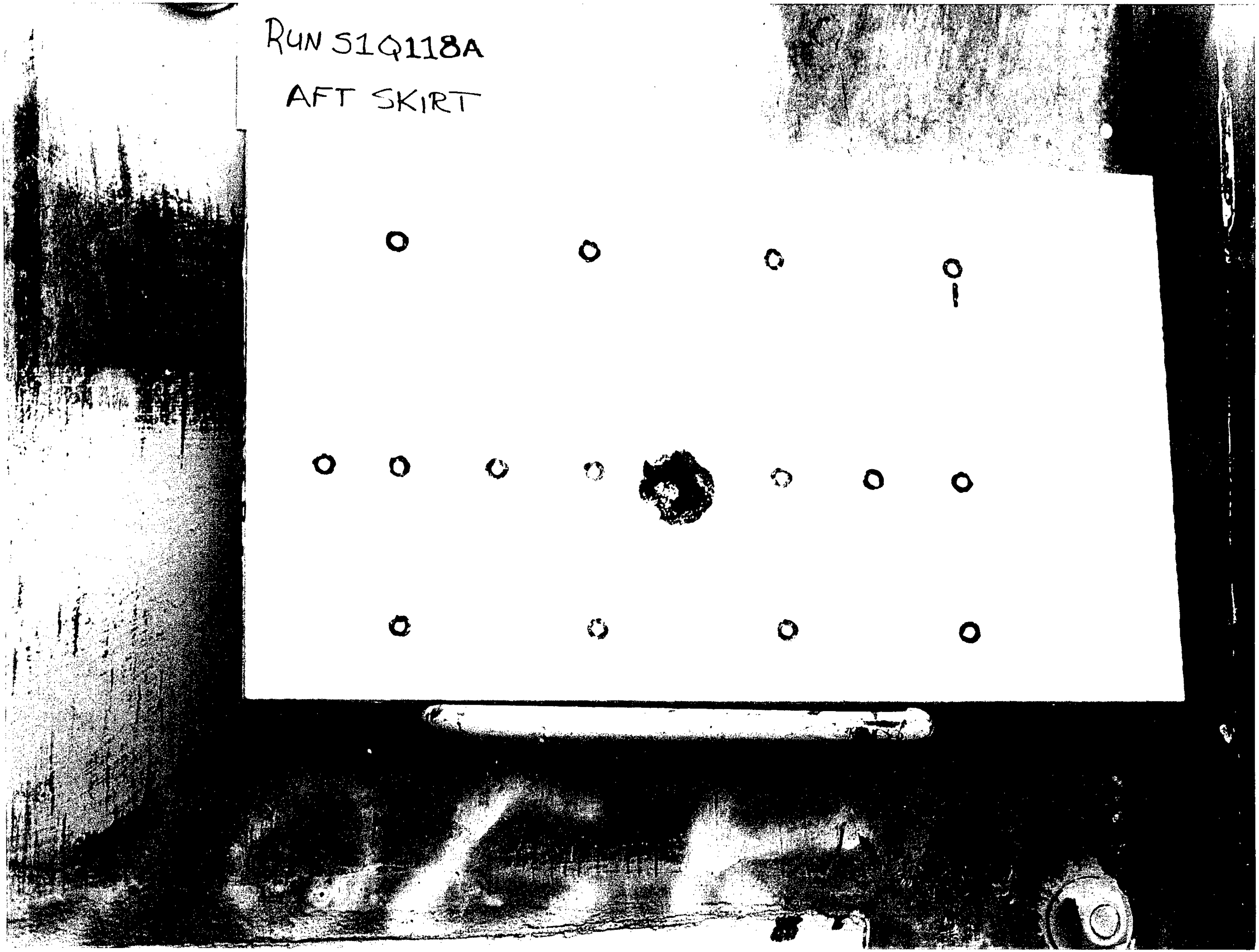


Figure B-15. Resultant Damage Due to Component A to Panel Q-11#8, Front View.

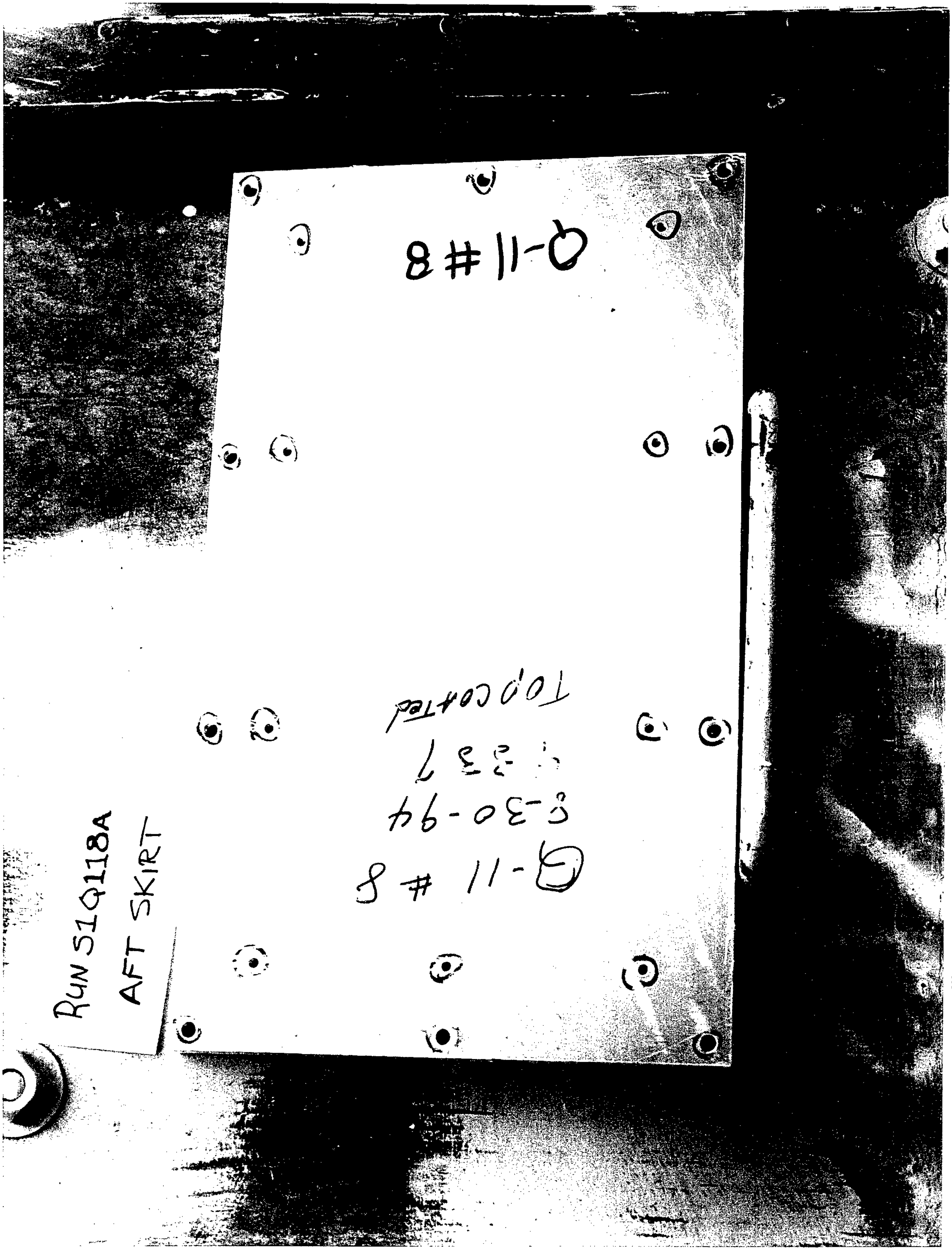


Figure B-16. Resultant Damage Due to Component A to Panel Q-11#8, Back View.

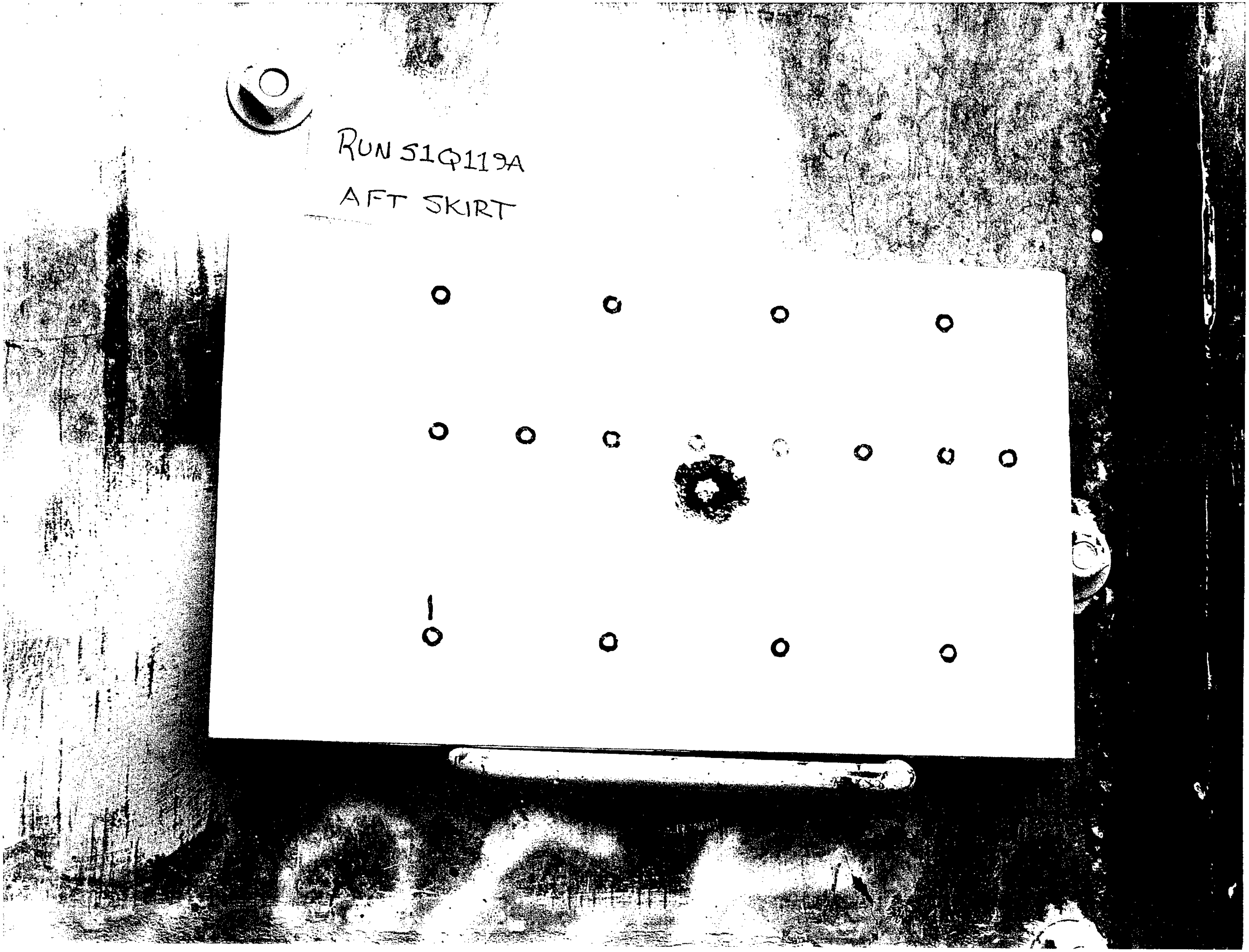


Figure B-17. Resultant Damage Due to Component A to Panel Q-11#9, Front View.

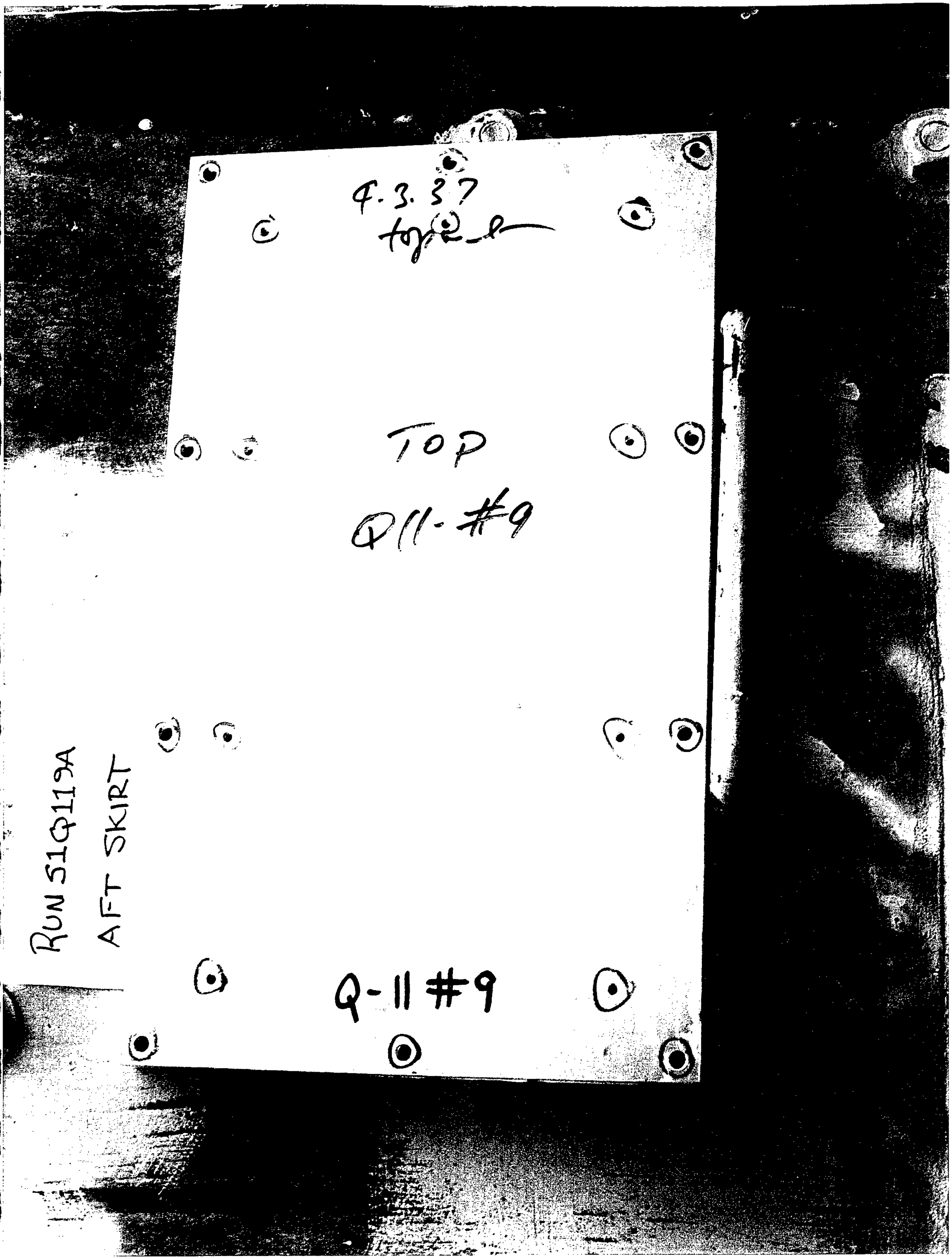


Figure B-18. Resultant Damage Due to Component A to Panel Q-11#9, Back View.

Figure B-19. Cumulative Damage Due to Components A and B to Panel Q-6#9, Front View.

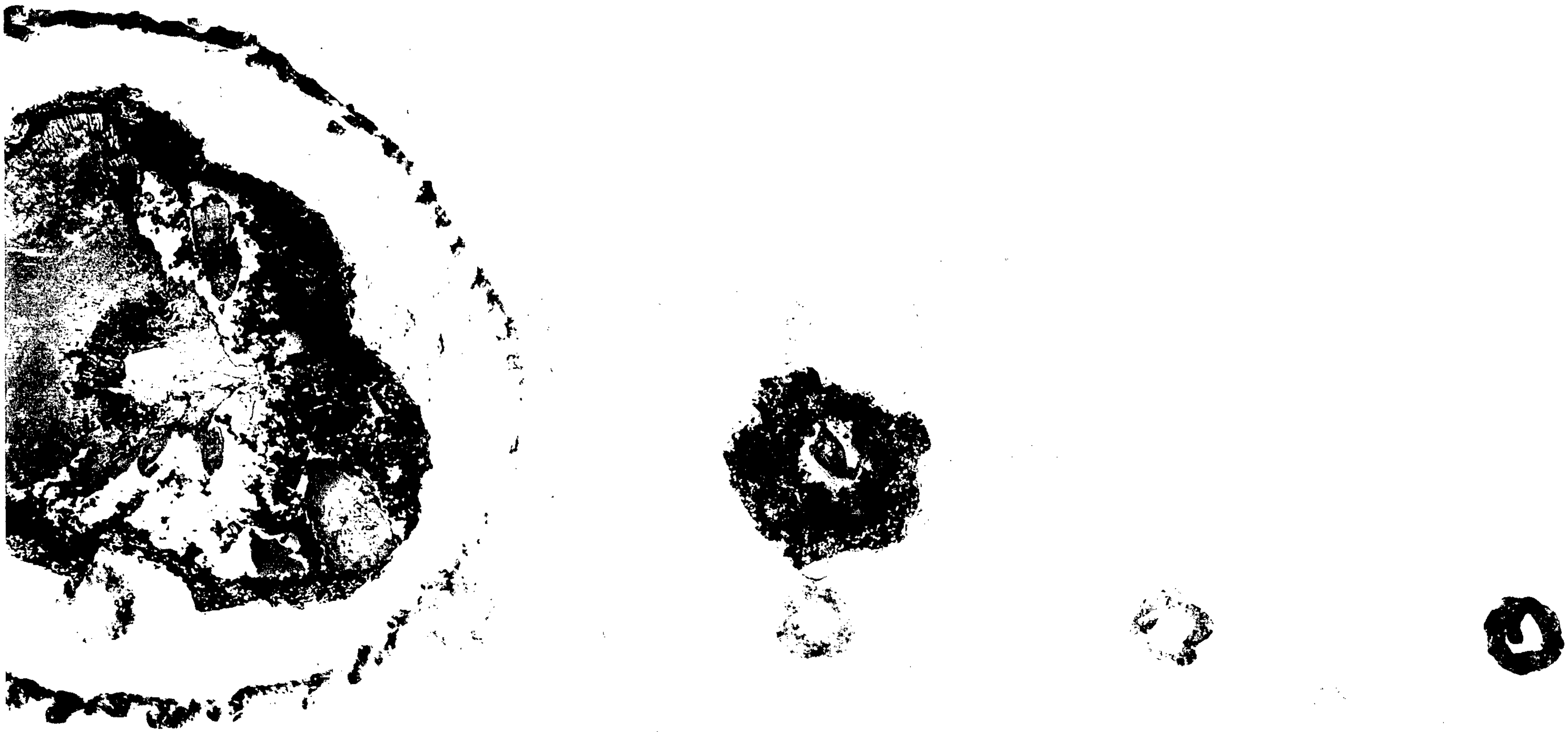


Figure B-20. Cumulative Damage Due to Components A and B to Panel Q-6#9, Close Up View.

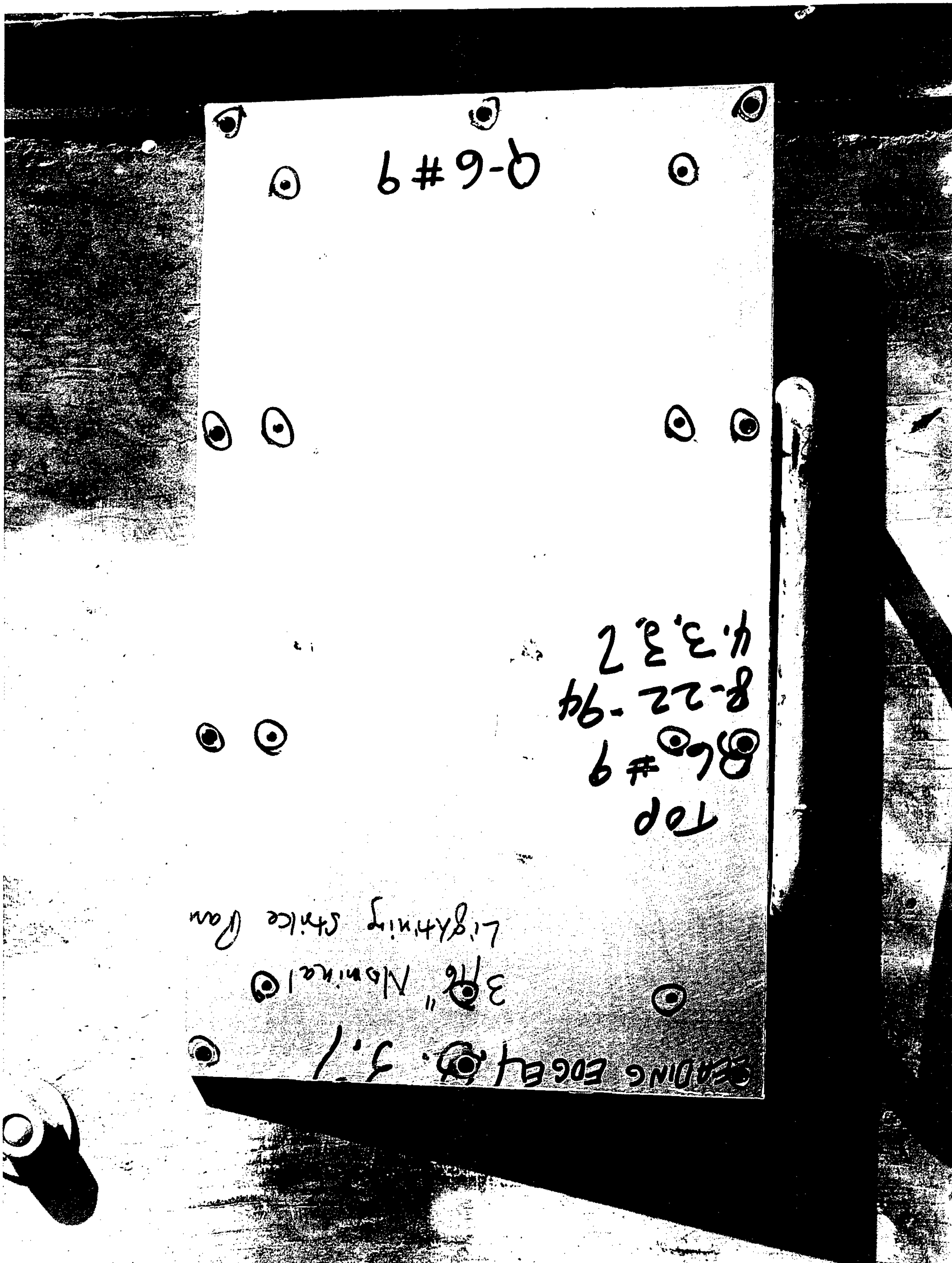


Figure B-21. Cumulative Damage Due to Components A and B to Panel Q-6#9, Back View.

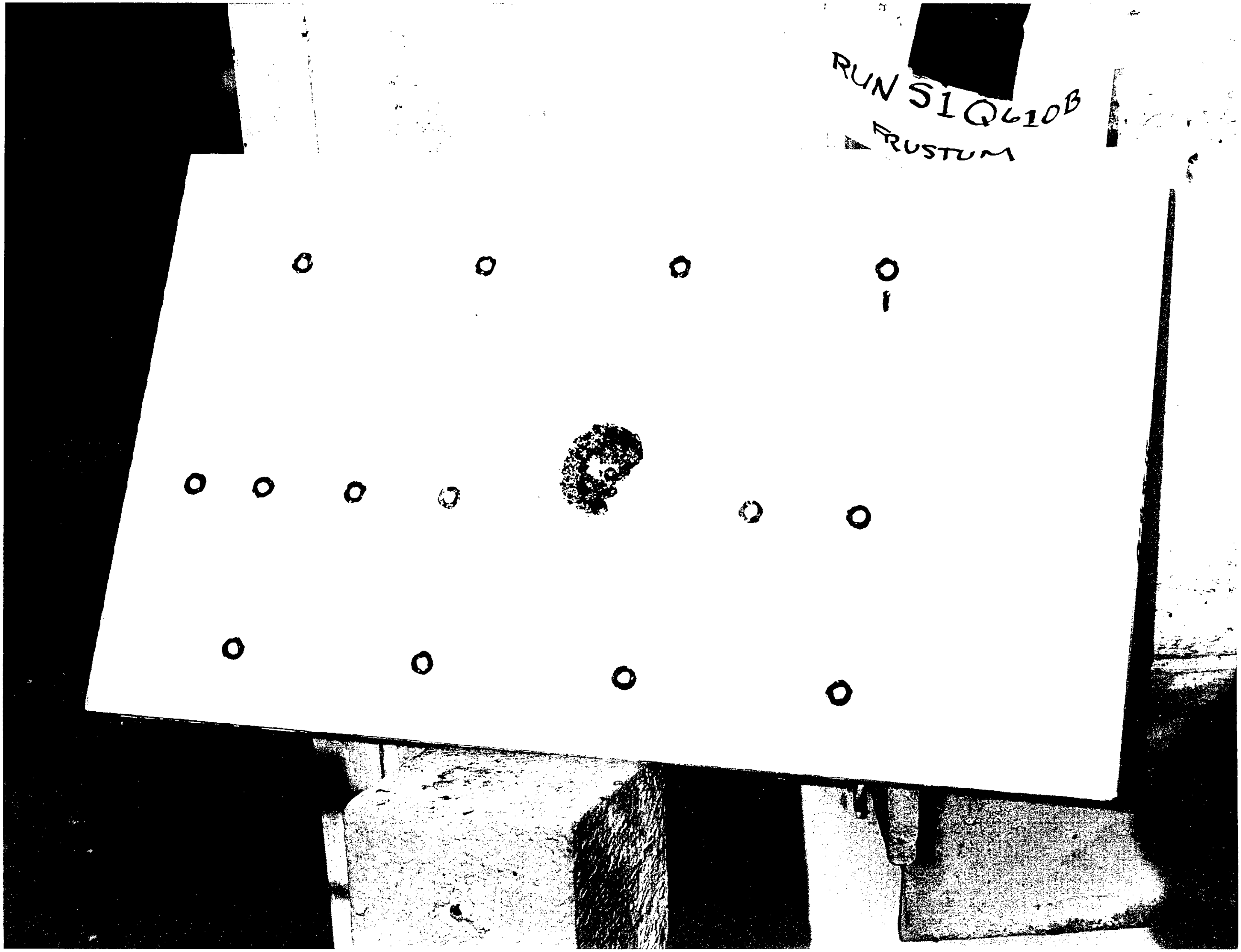


Figure B-22. Cumulative Damage Due to Components A and B to Panel Q-6#10, Front View.

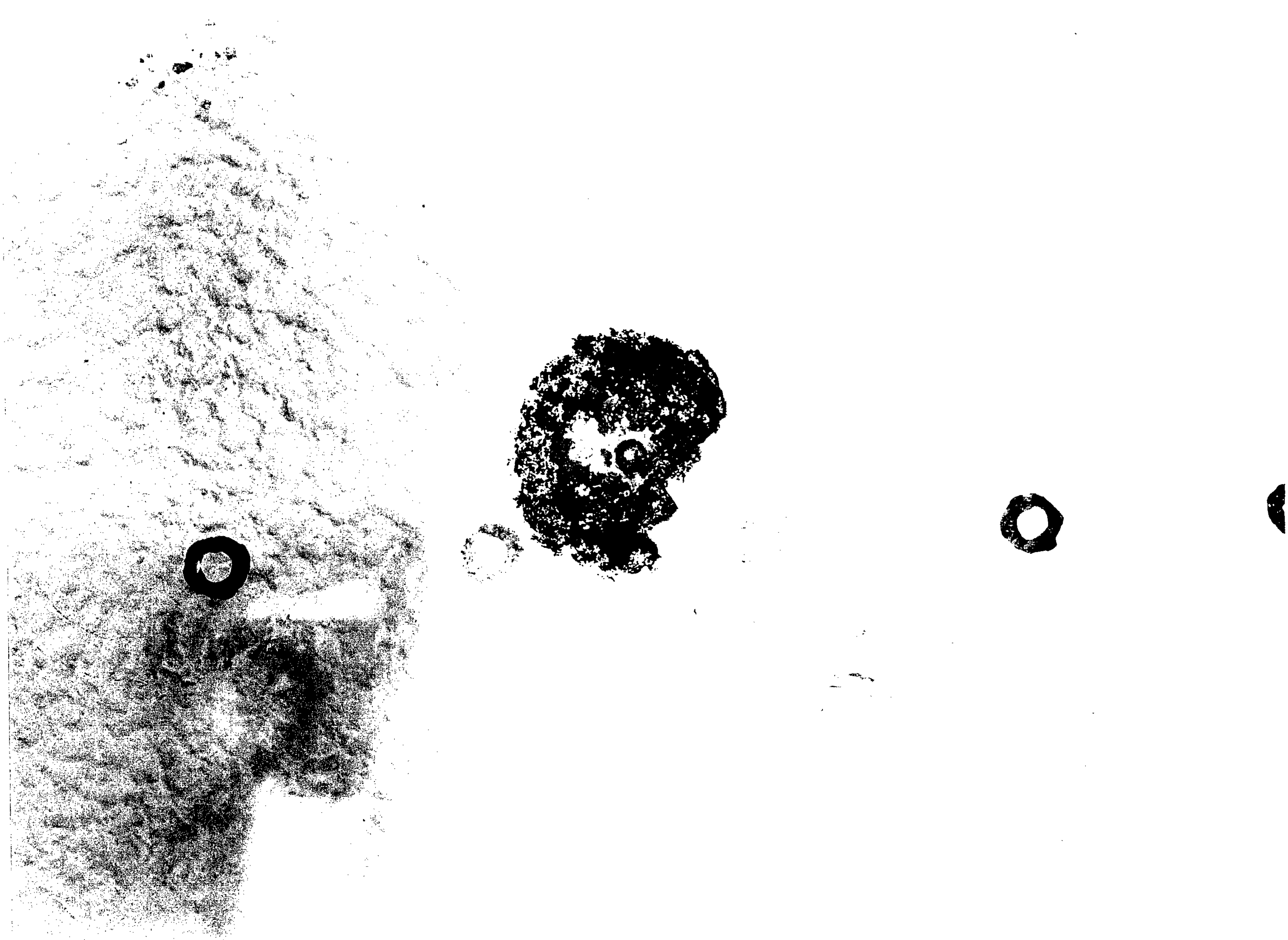


Figure B-23. Cumulative Damage Due to Components A and B to Panel Q-6#10, Close Up View.

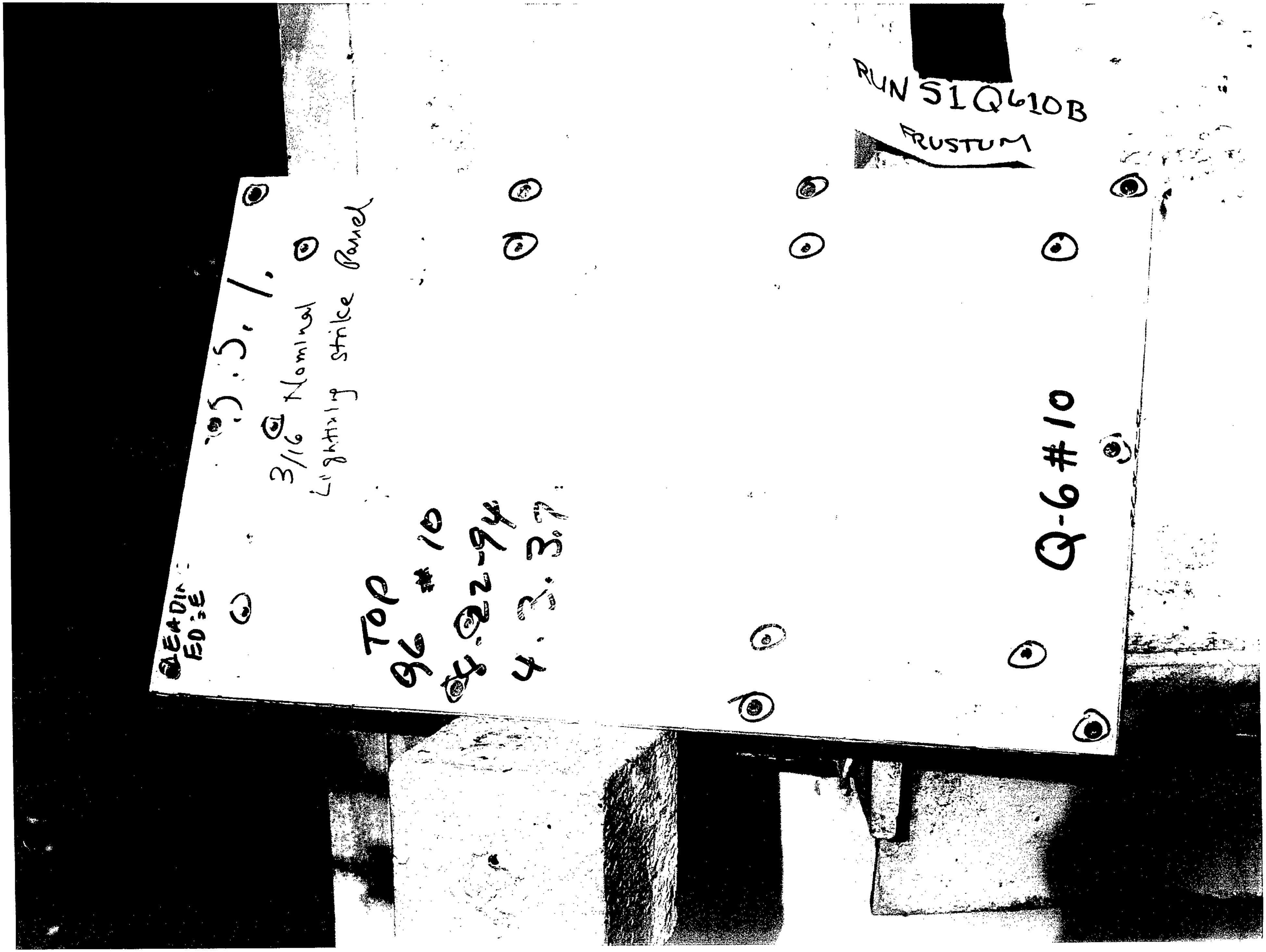


Figure B-24. Cumulative Damage Due to Components A and B to Panel Q-6#10, Back View.

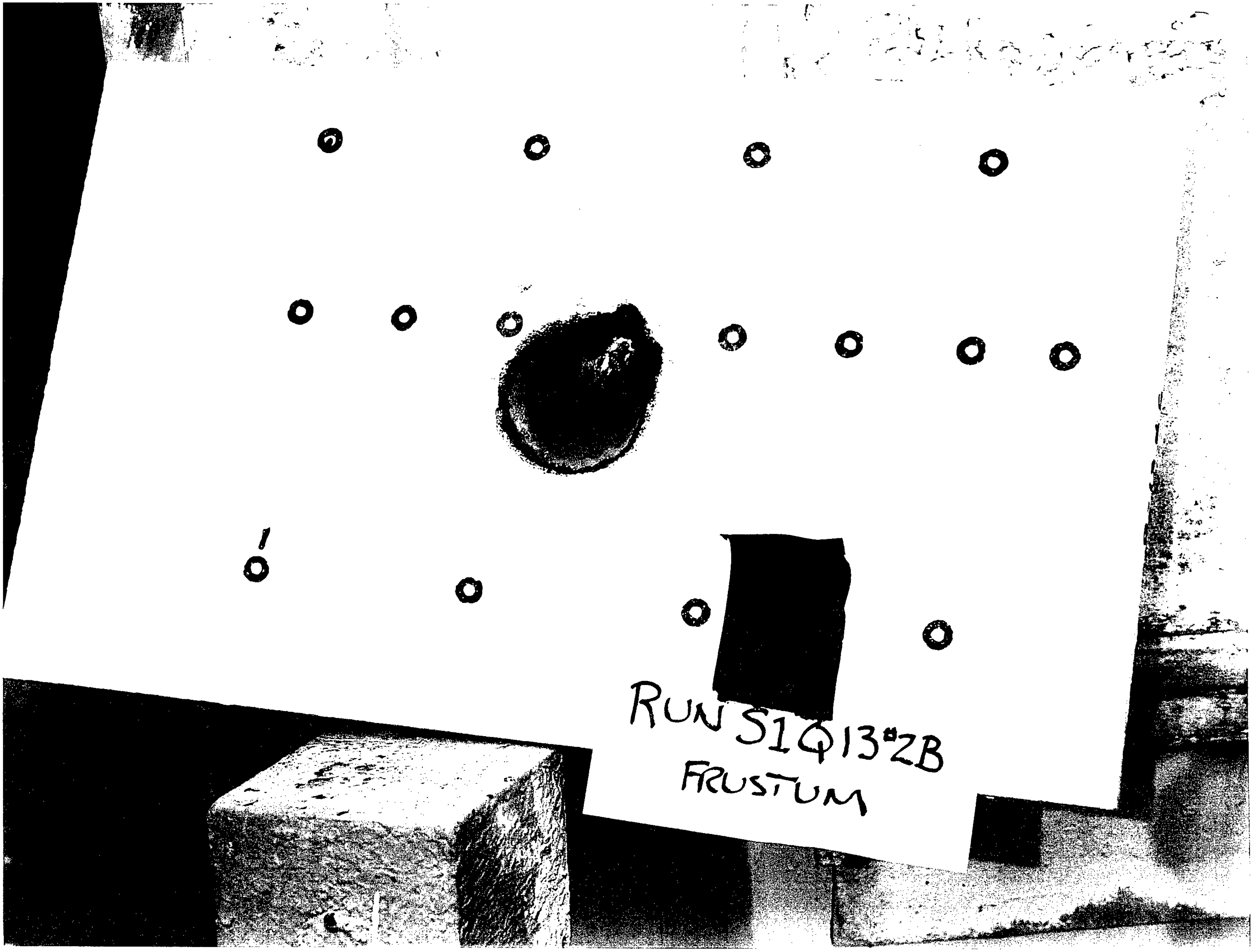


Figure B-25. Cumulative Damage Due to Components A and B to Panel Q-13#2, Front View.

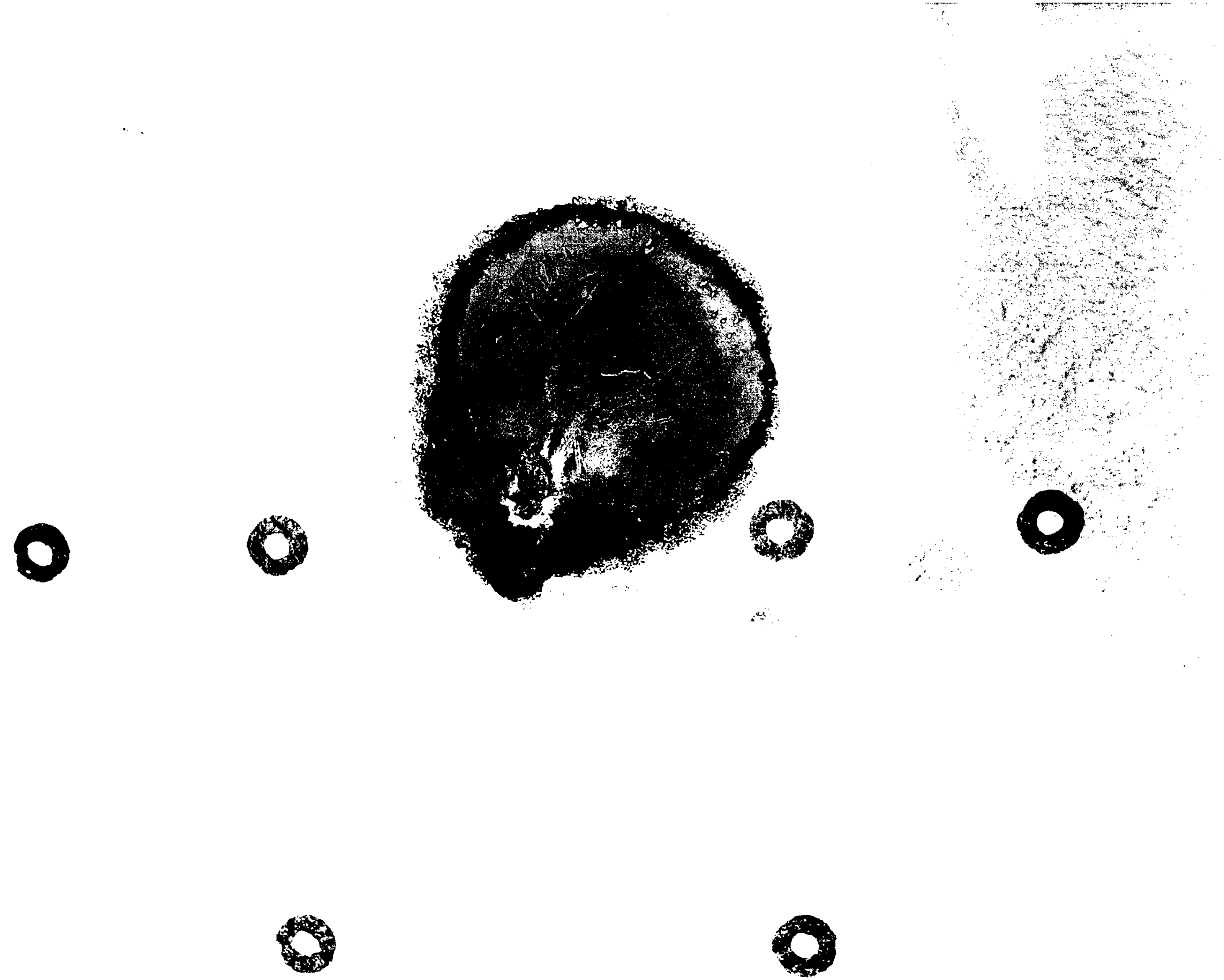


Figure B-26. Cumulative Damage Due to Components A and B to Panel Q-13#2, Close Up View.

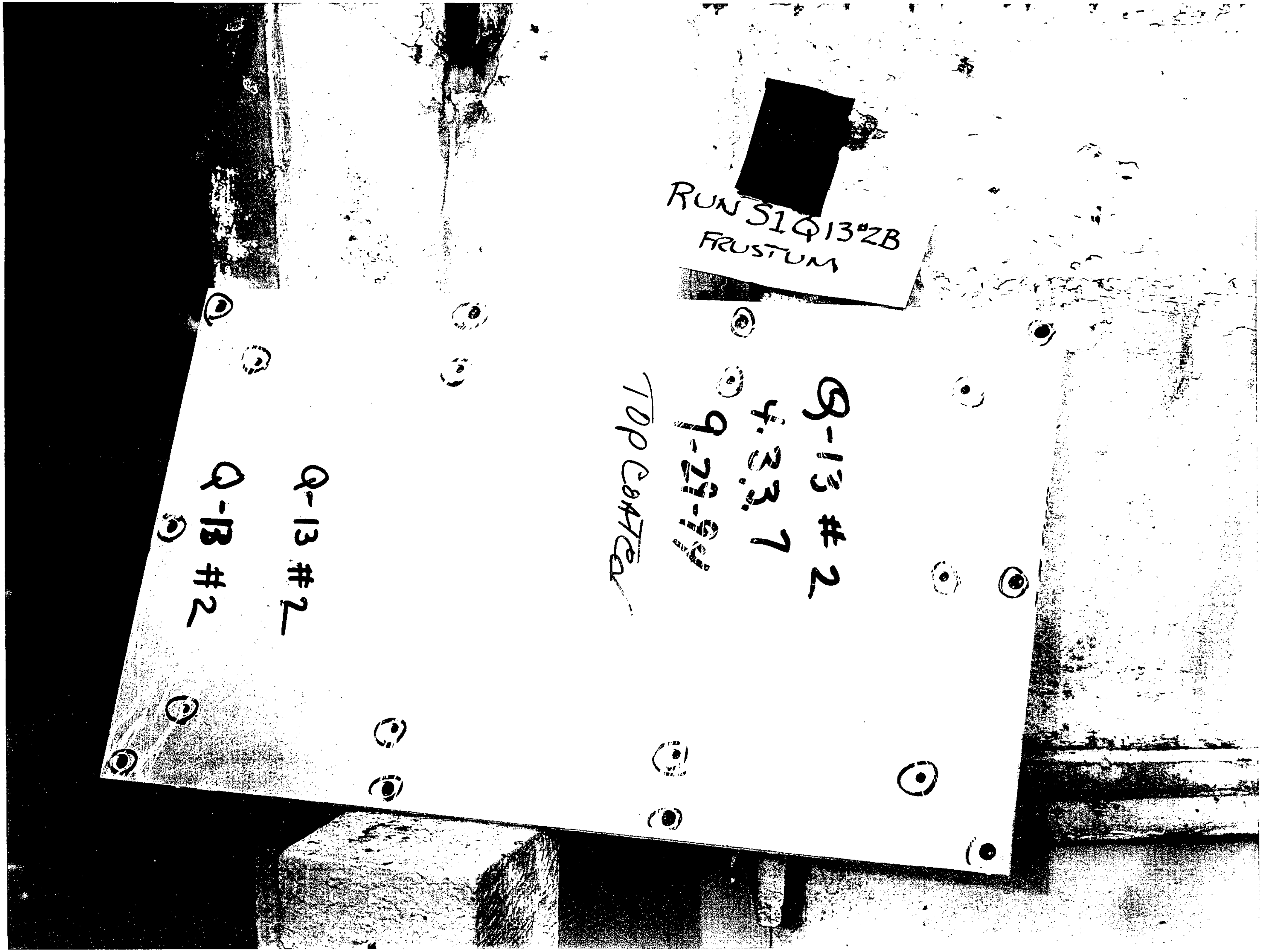


Figure B-27. Cumulative Damage Due to Components A and B to Panel Q-13#2, Back View.

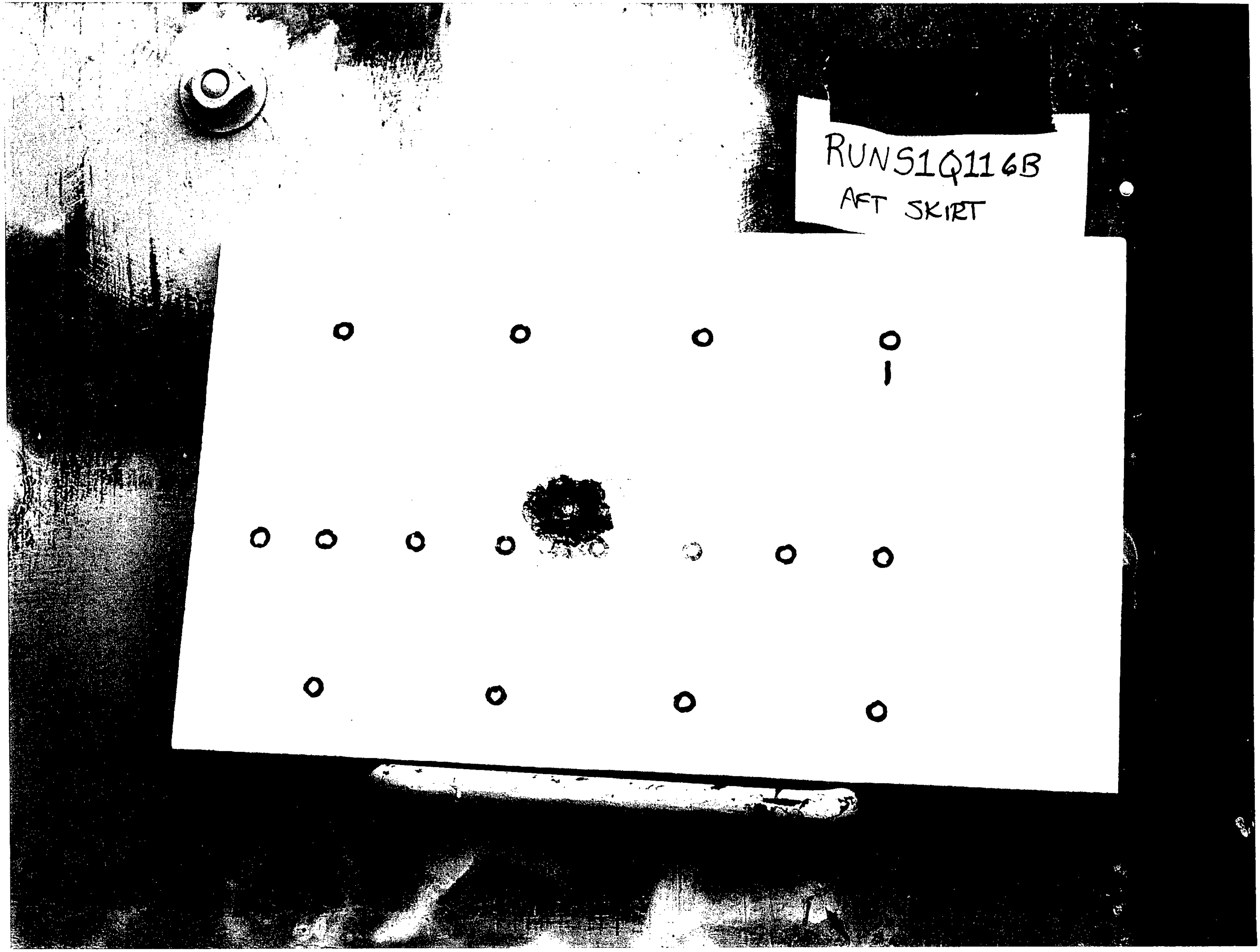


Figure B-28. Cumulative Damage Due to Components A and B to Panel Q-11#6, Front View.

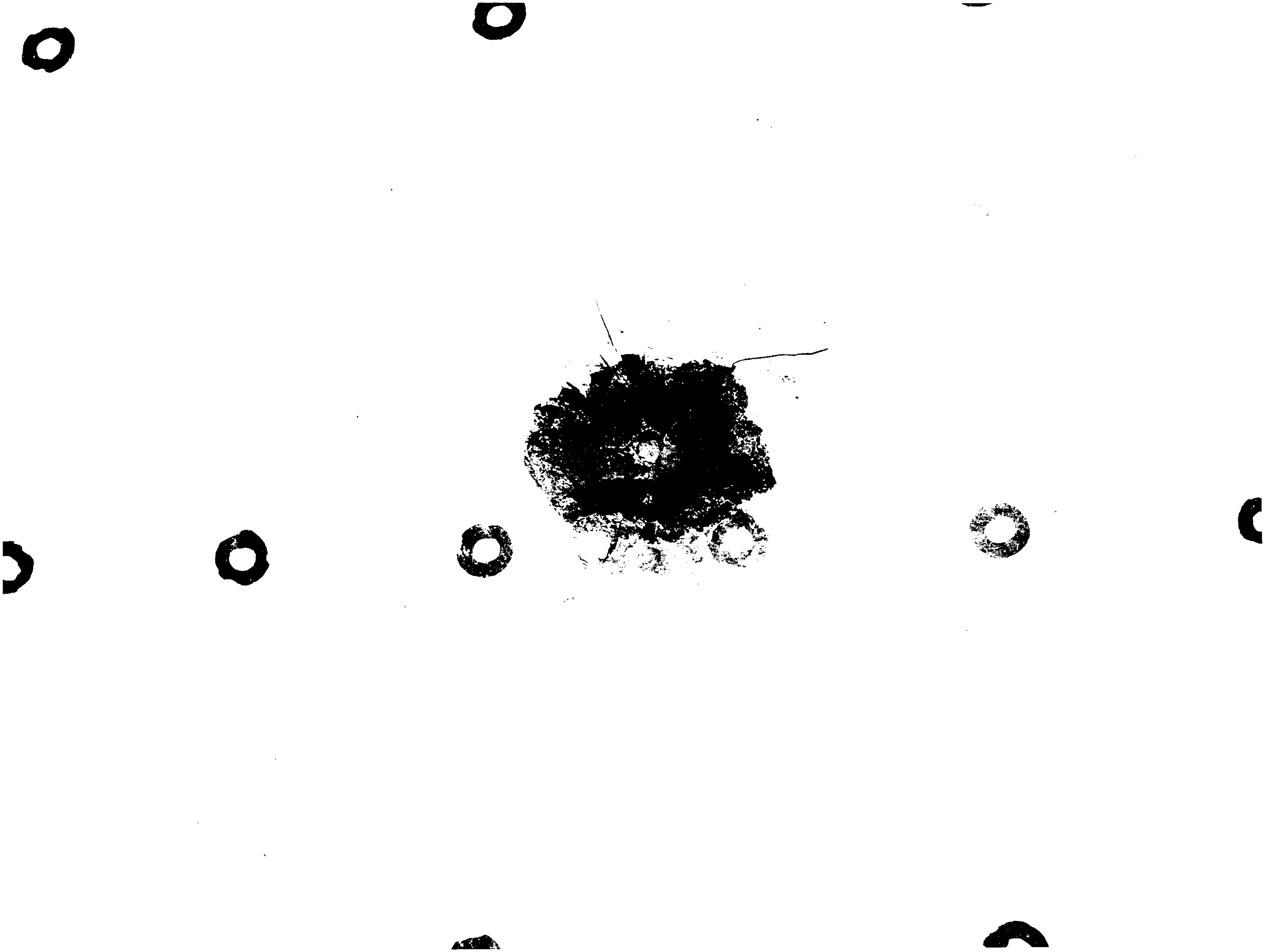


Figure B-29. Cumulative Damage Due to Components A and B to Panel Q-11#6, Close Up View.

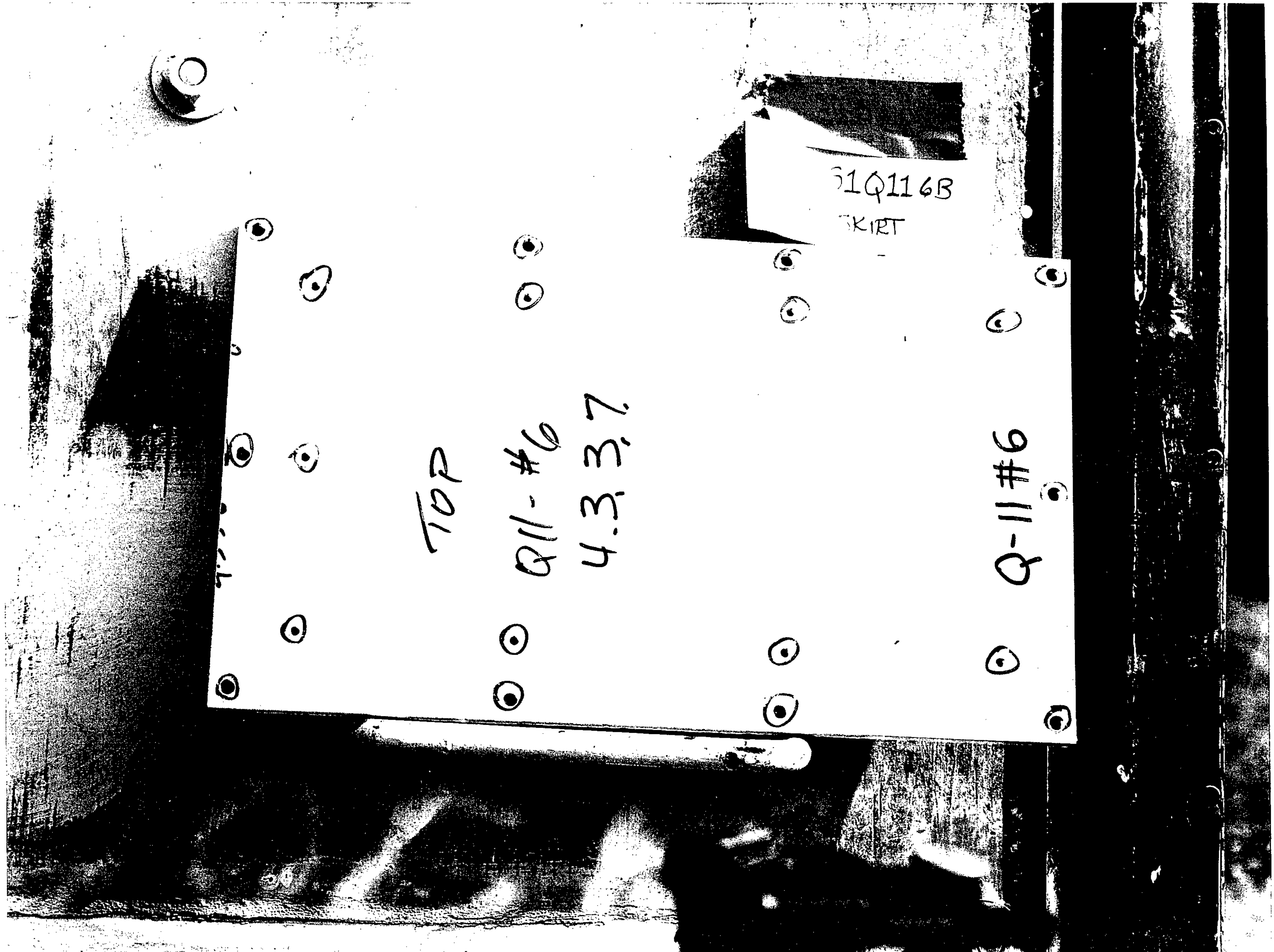


Figure B-30. Cumulative Damage Due to Components A and B to Panel Q-11#6, Back View.

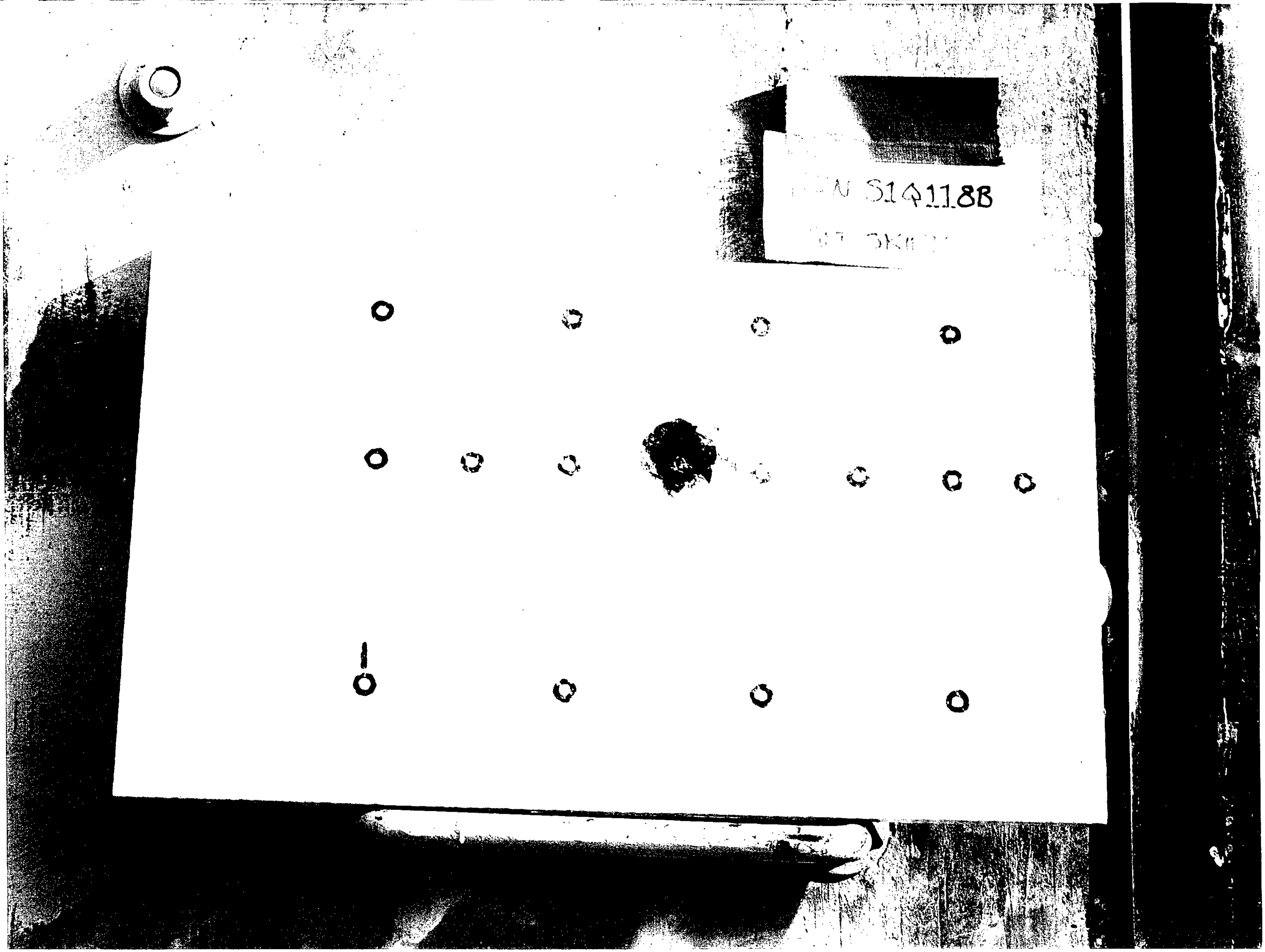


Figure B-31. Cumulative Damage Due to Components A and B to Panel Q-11#8, Front View.

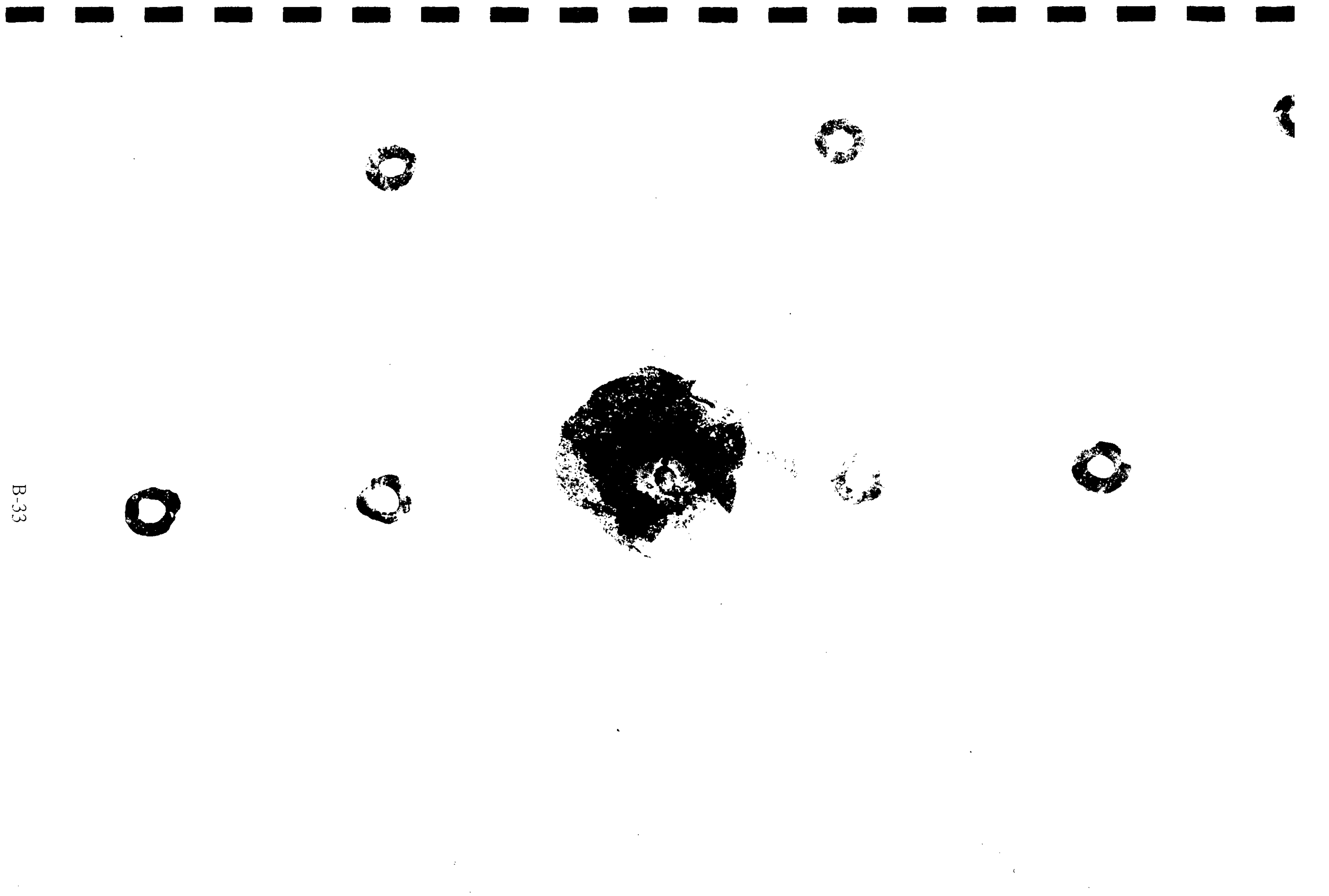


Figure B-32. Cumulative Damage Due to Components A and B to Panel Q-11#8, Close Up View.

Figure B-33. Cumulative Damage Due to Components A and B to Panel Q-11#8, Back View.

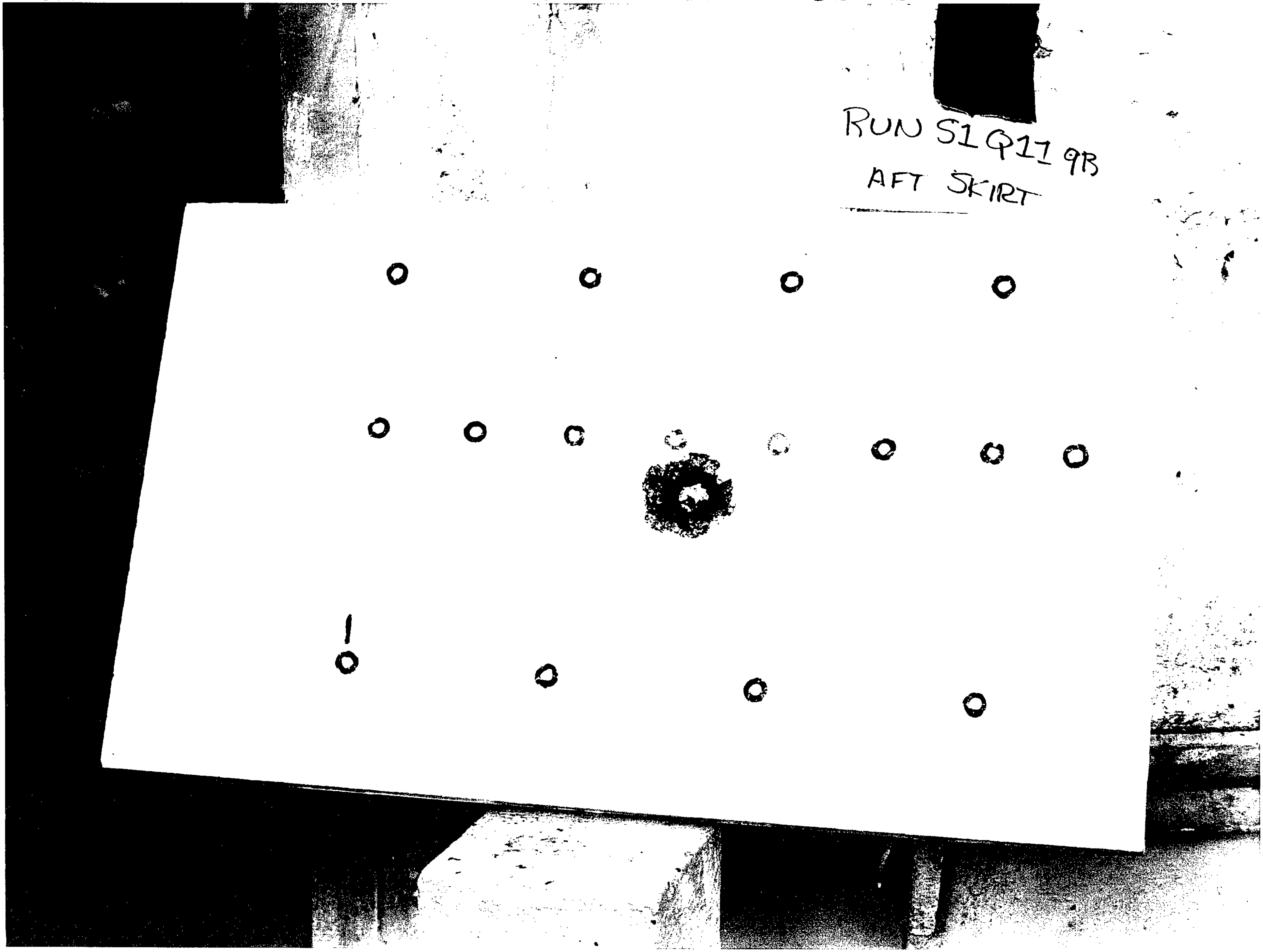


Figure B-34. Cumulative Damage Due to Components A and B to Panel Q-11#9, Front View.

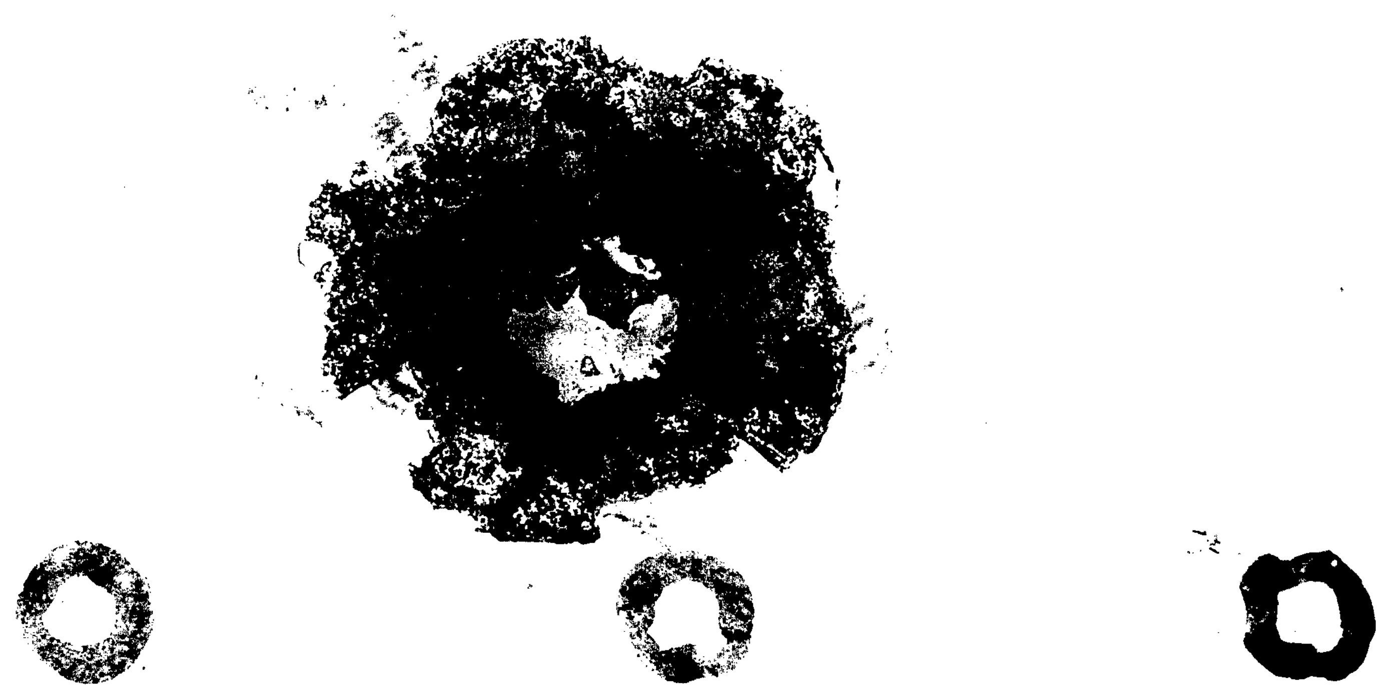


Figure B-35. Cumulative Damage Due to Components A and B to Panel Q-11#9, Close Up View.

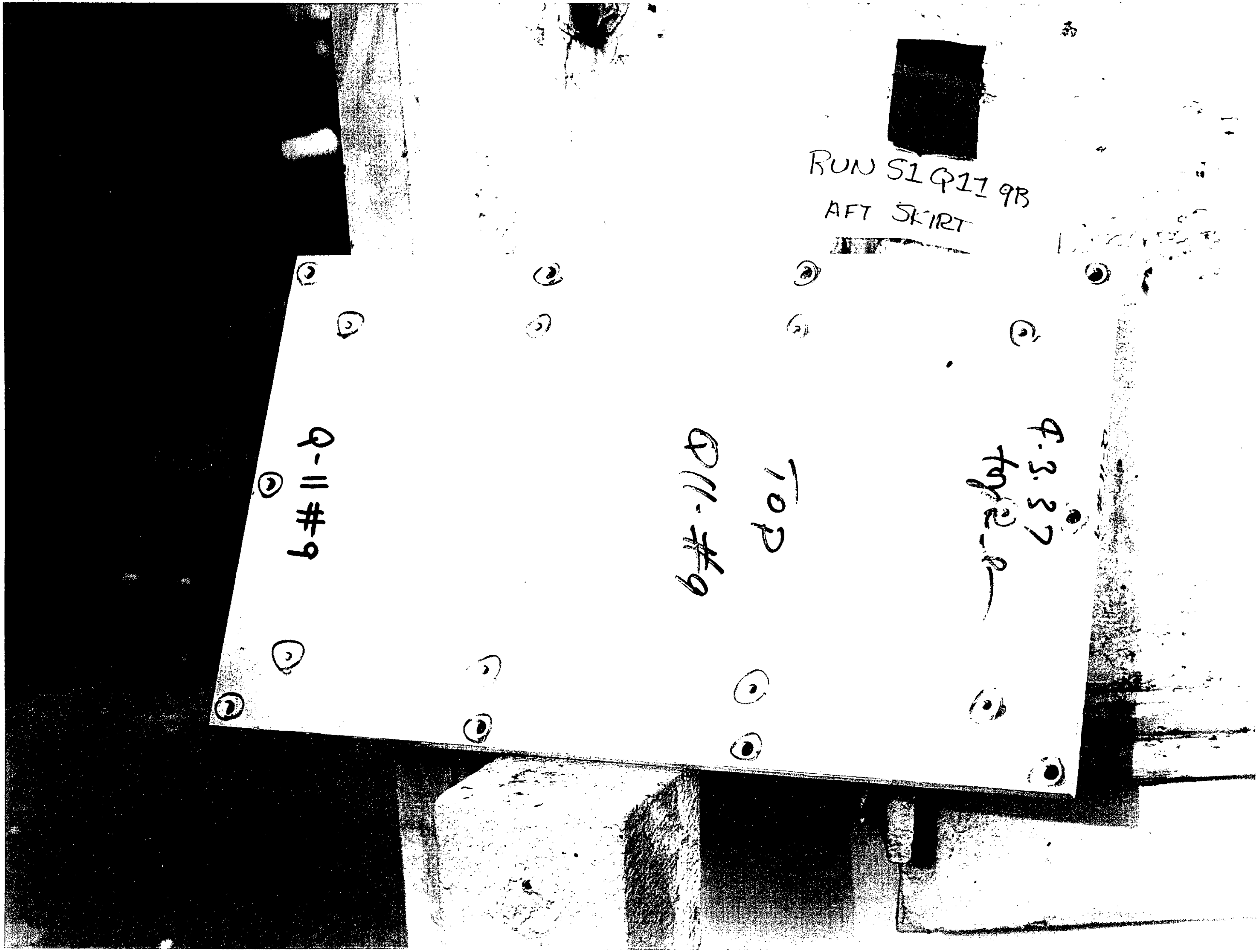


Figure B-36. Cumulative Damage Due to Components A and B to Panel Q-11#9. Back View.

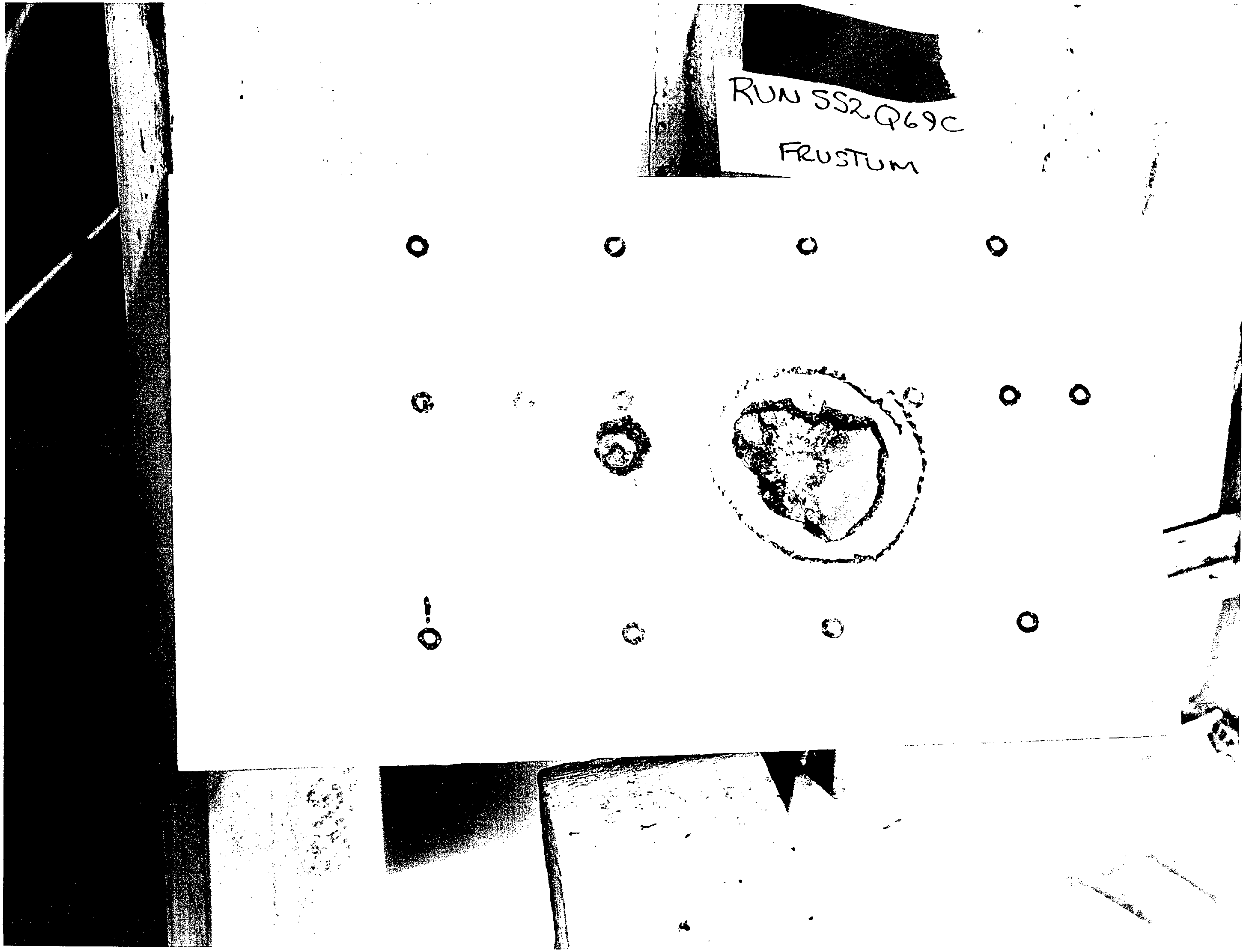


Figure B-37. Cumulative Damage Due to Components A, B, and C to Panel Q-6#9, Front View.

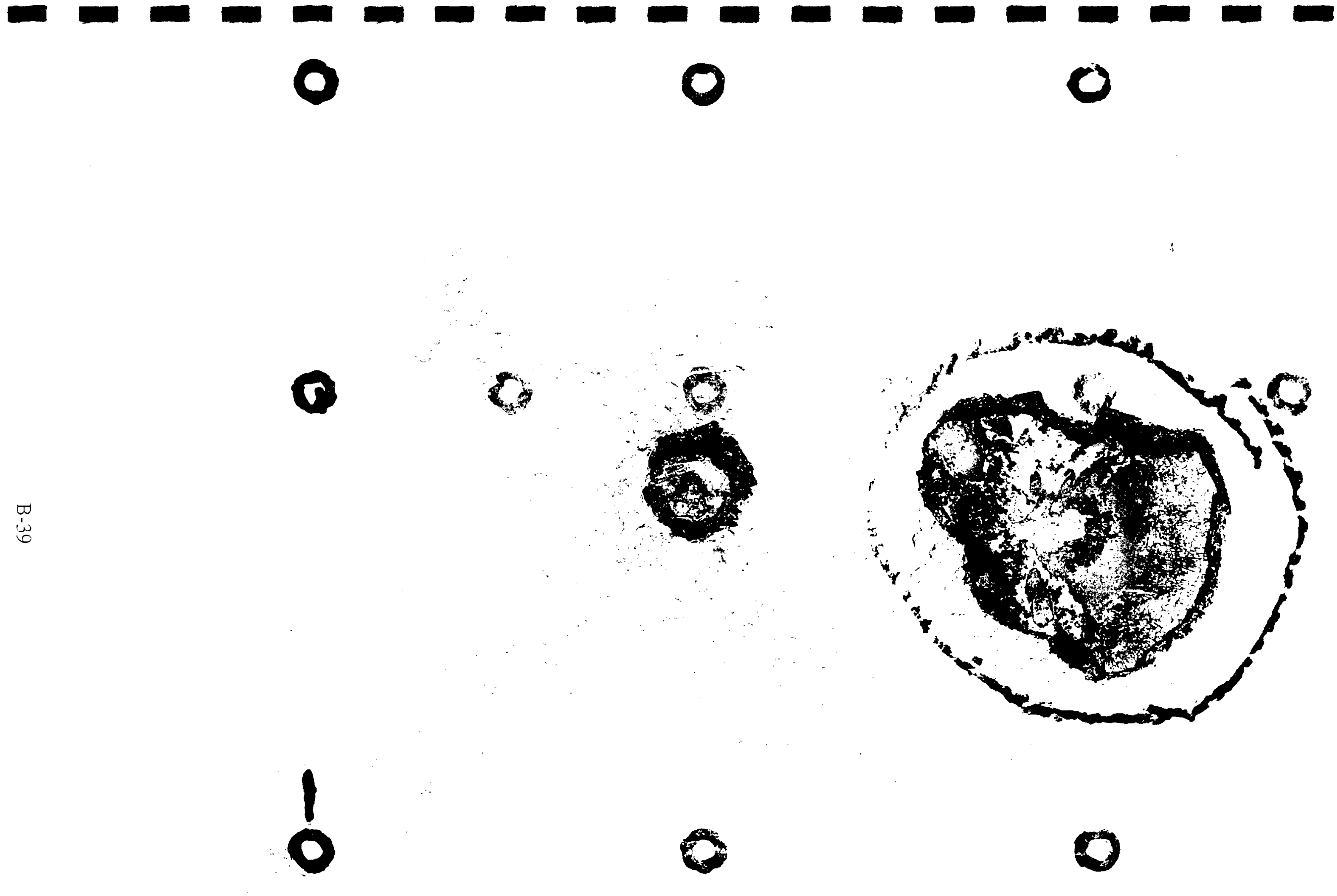


Figure B-38. Cumulative Damage Due to Components A, B, and C to Panel Q-6#9, Close Up View.

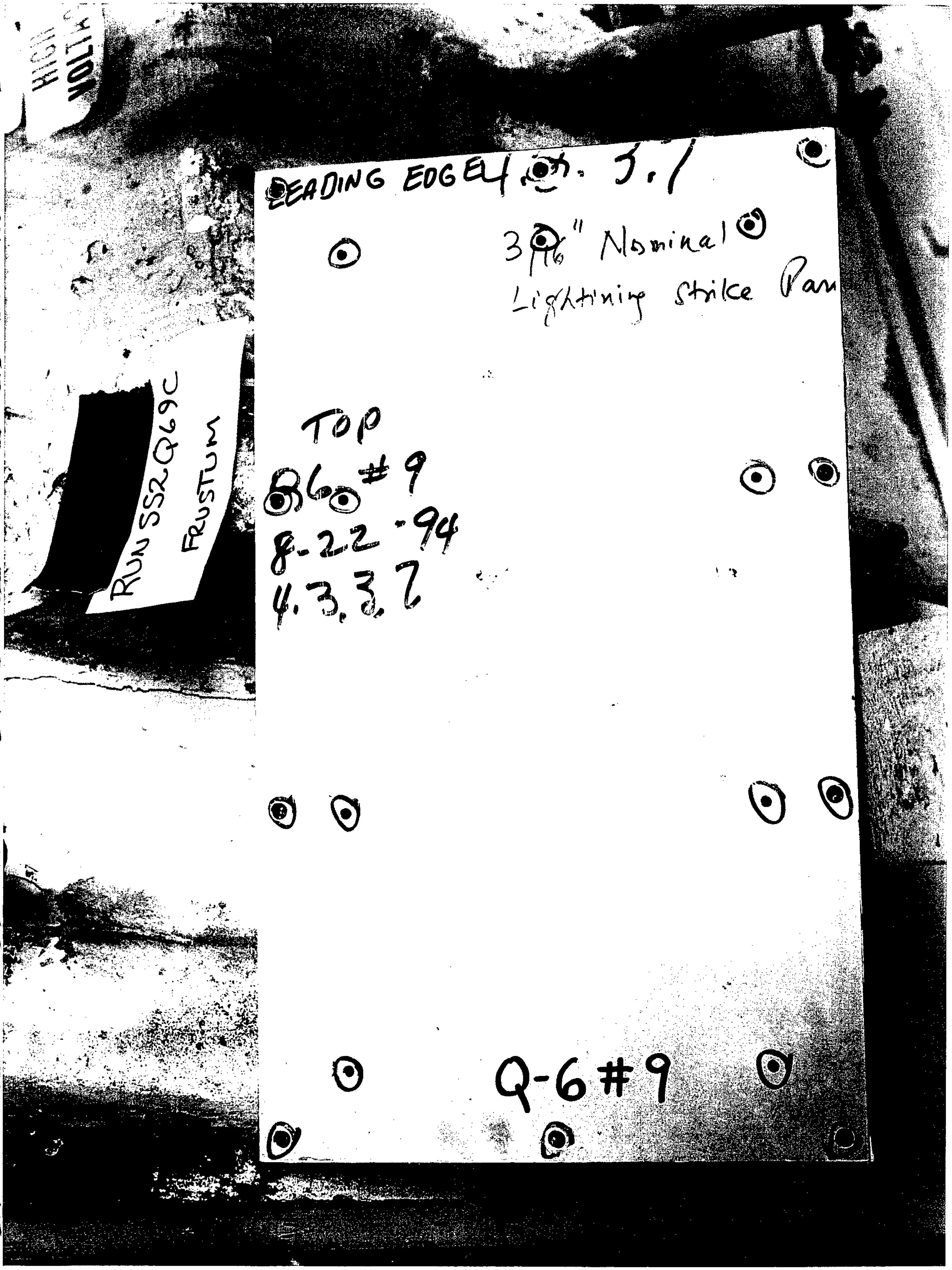


Figure B-39. Cumulative Damage Due to Components A, B, and C to Panel Q-6#9, Back View.

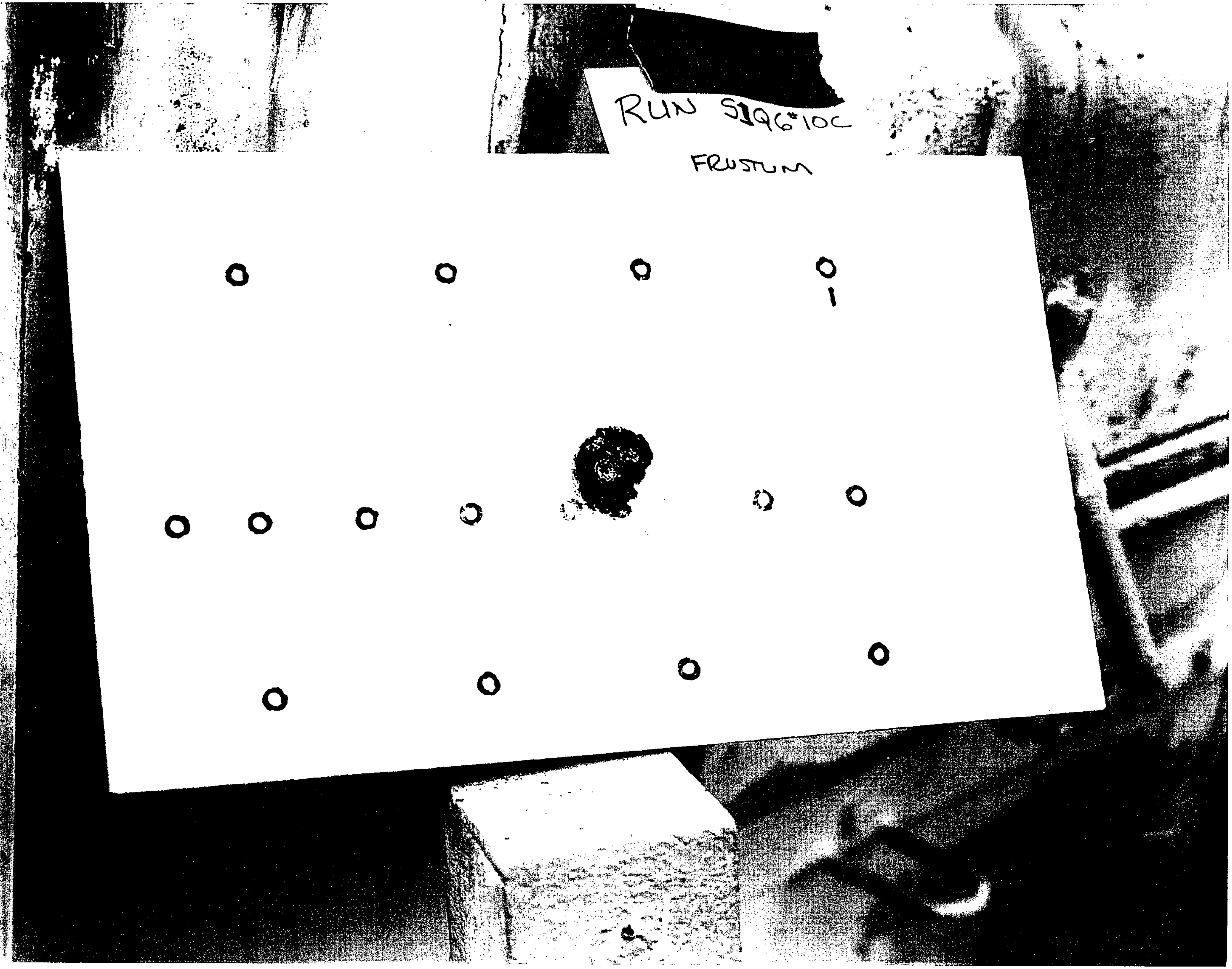


Figure B-40. Cumulative Damage Due to Components A, B, and C to Panel Q-6#10, Front View.

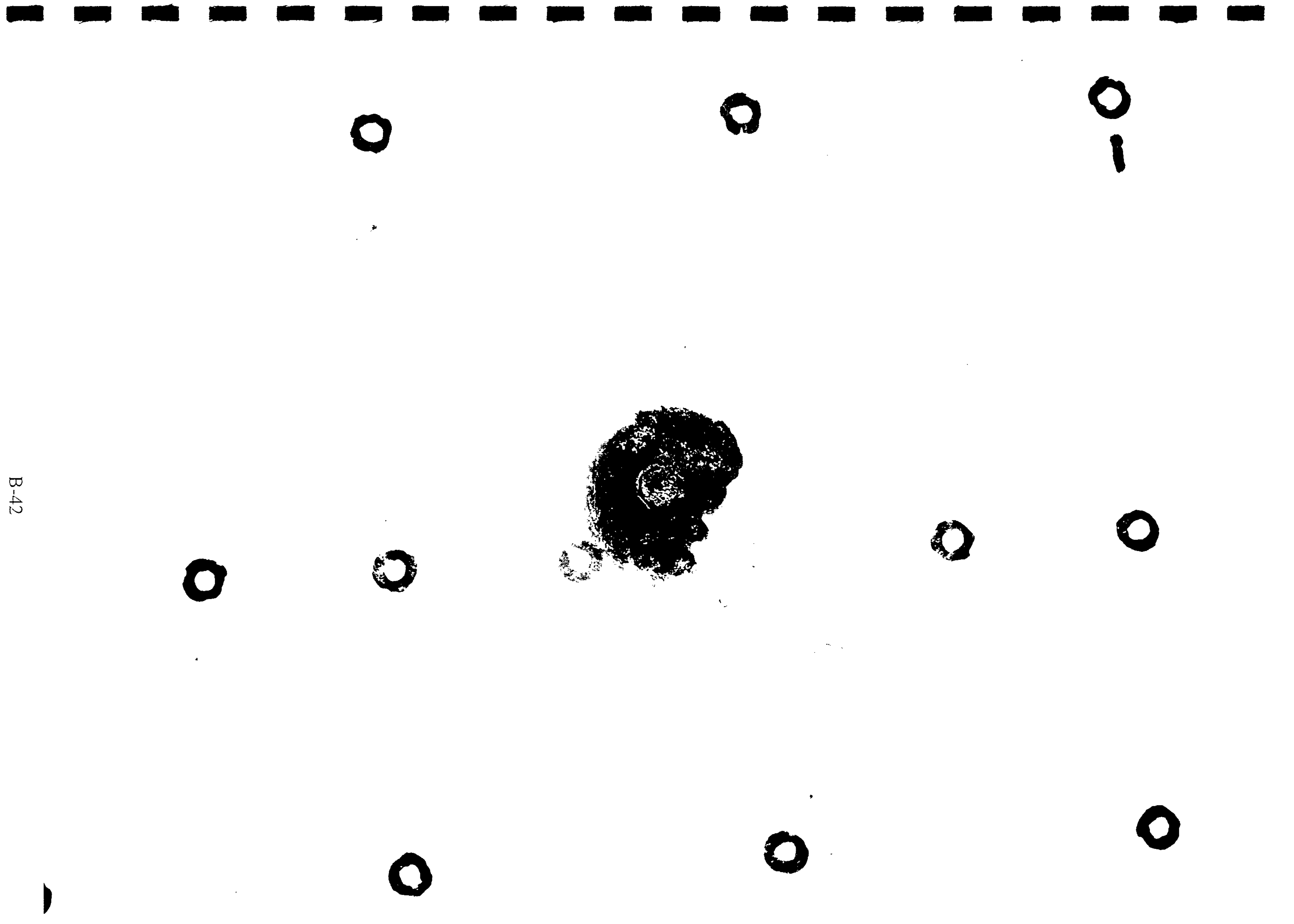


Figure B-41. Cumulative Damage Due to Components A, B, and C to Panel Q-6#10, Close Up View.

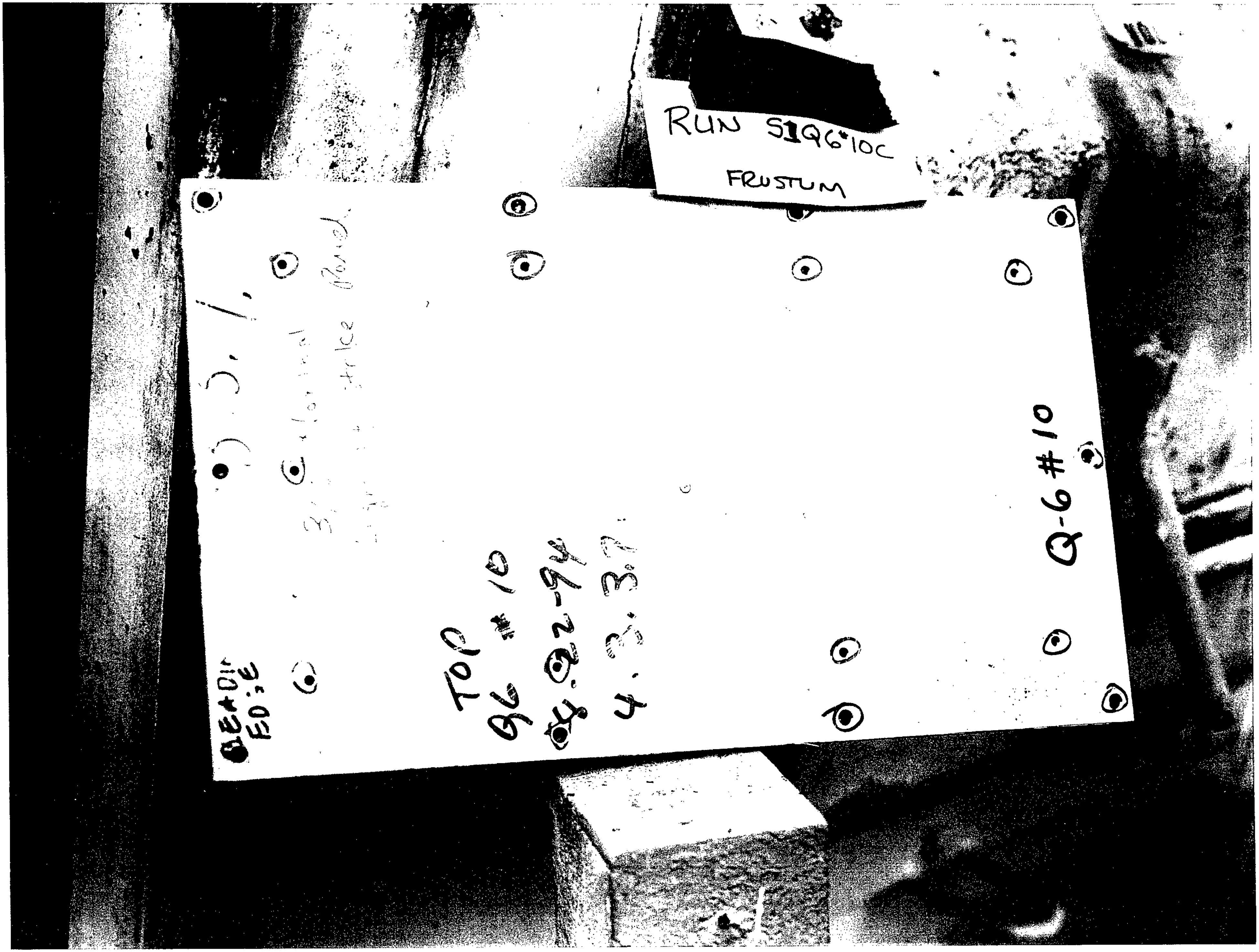


Figure B-42. Cumulative Damage Due to Components A, B, and C to Panel Q-6#10, Back View.

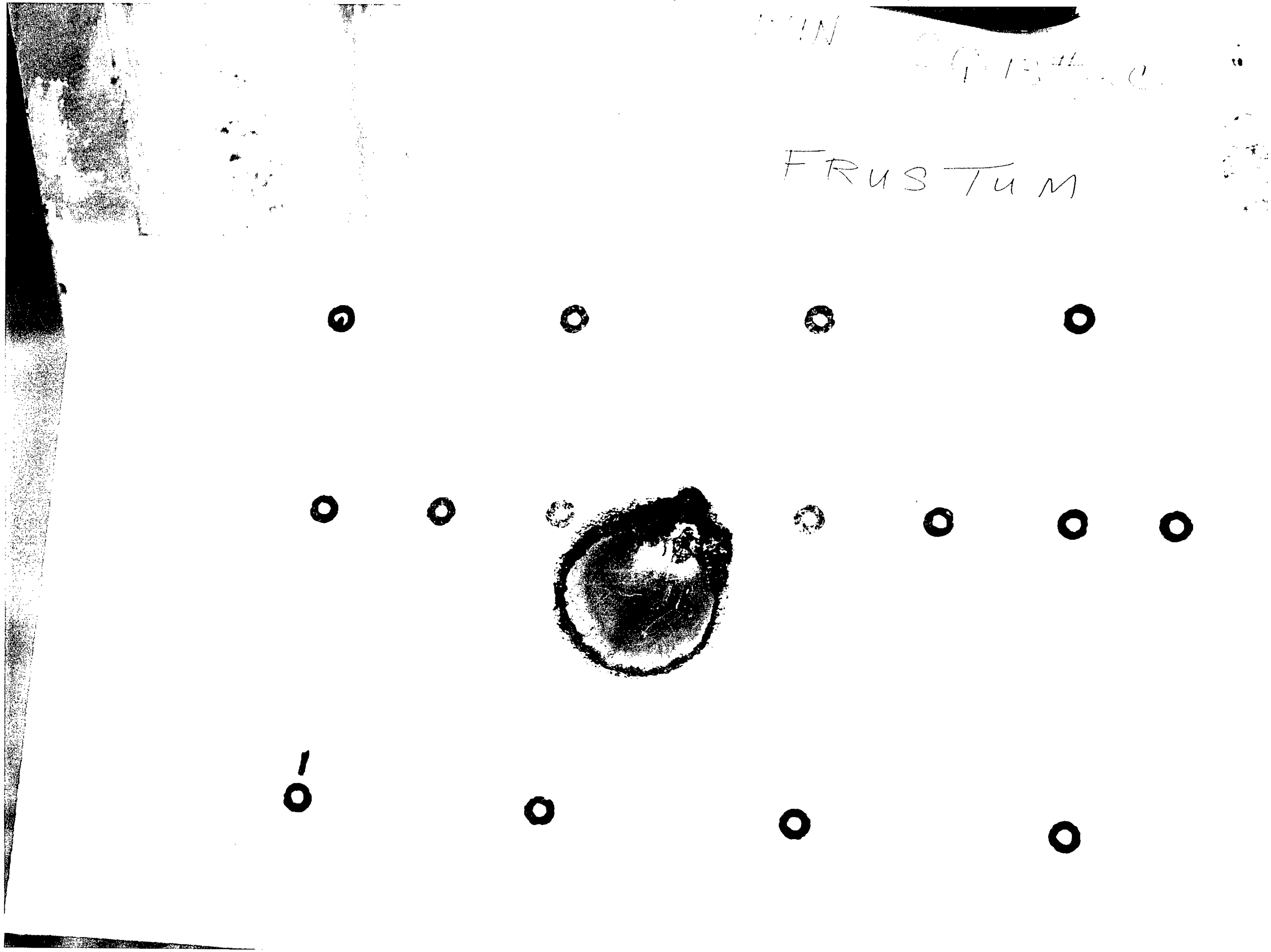


Figure B-43. Cumulative Damage Due to Components A, B, and C to Panel Q-13#2, Front View.

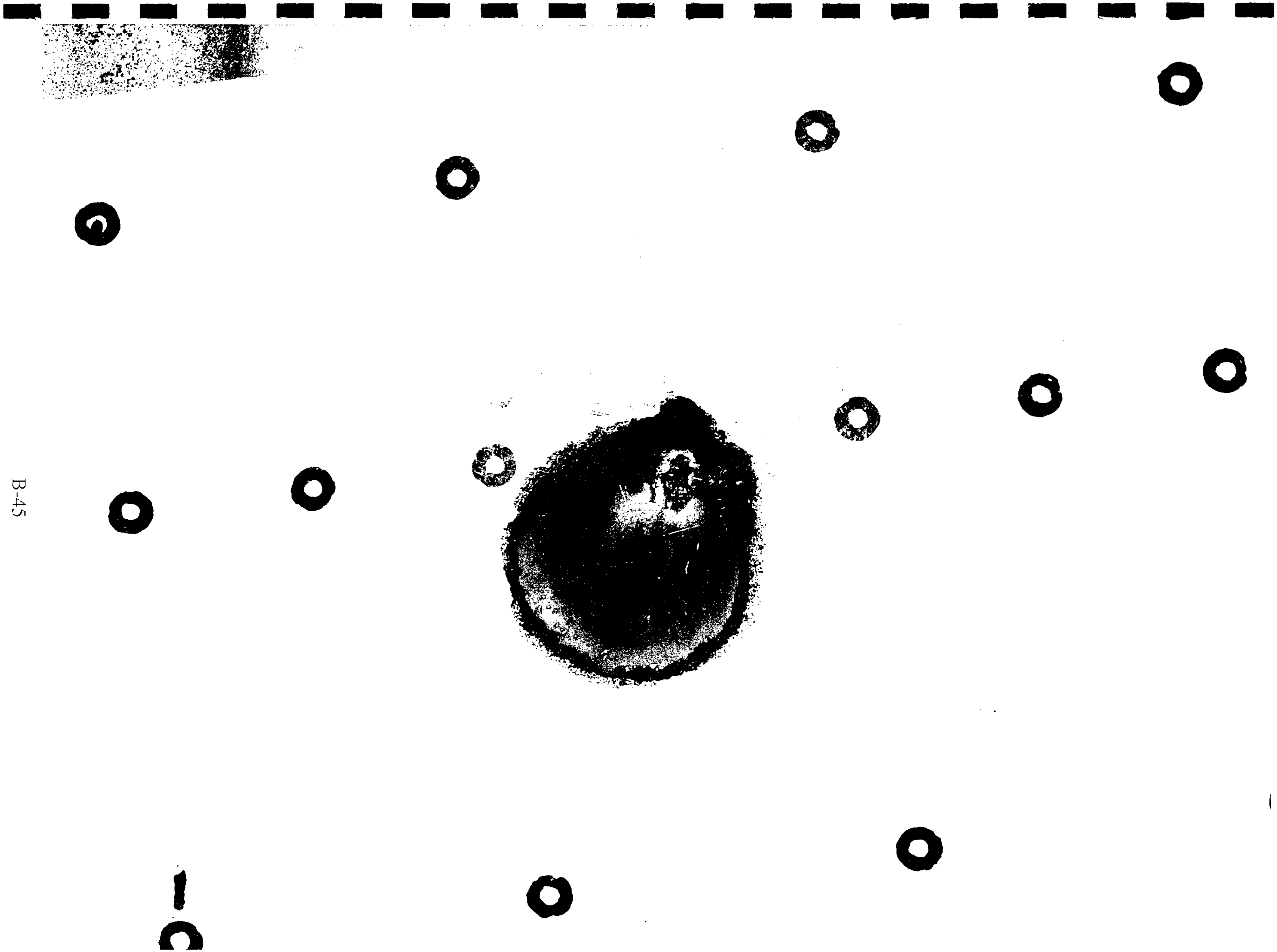


Figure B-44. Cumulative Damage Due to Components A, B, and C to Panel Q-13#2, Close Up View.

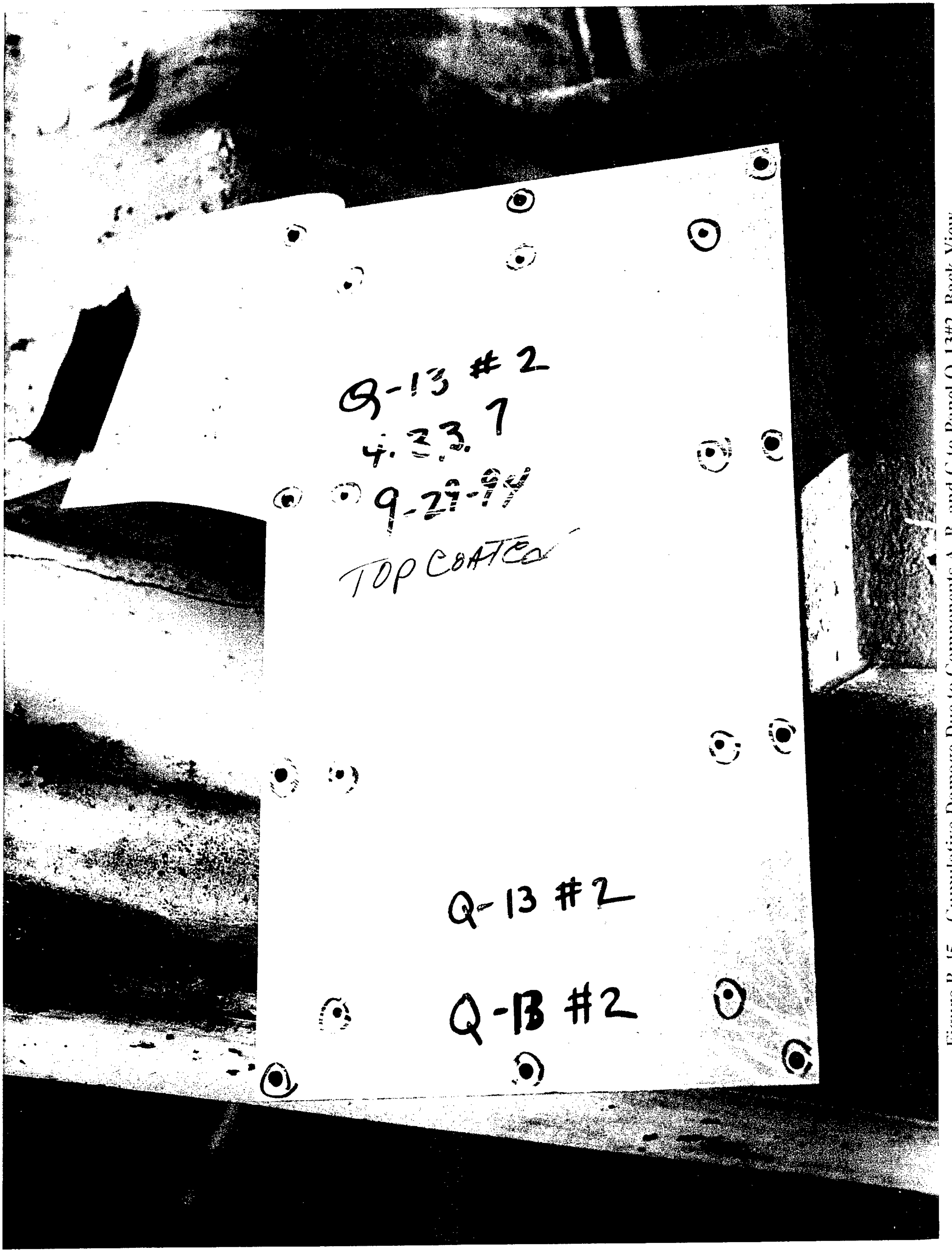


Figure B-45. Cumulative Damage Due to Components A, B, and C to Panel Q-13#2, Back View.

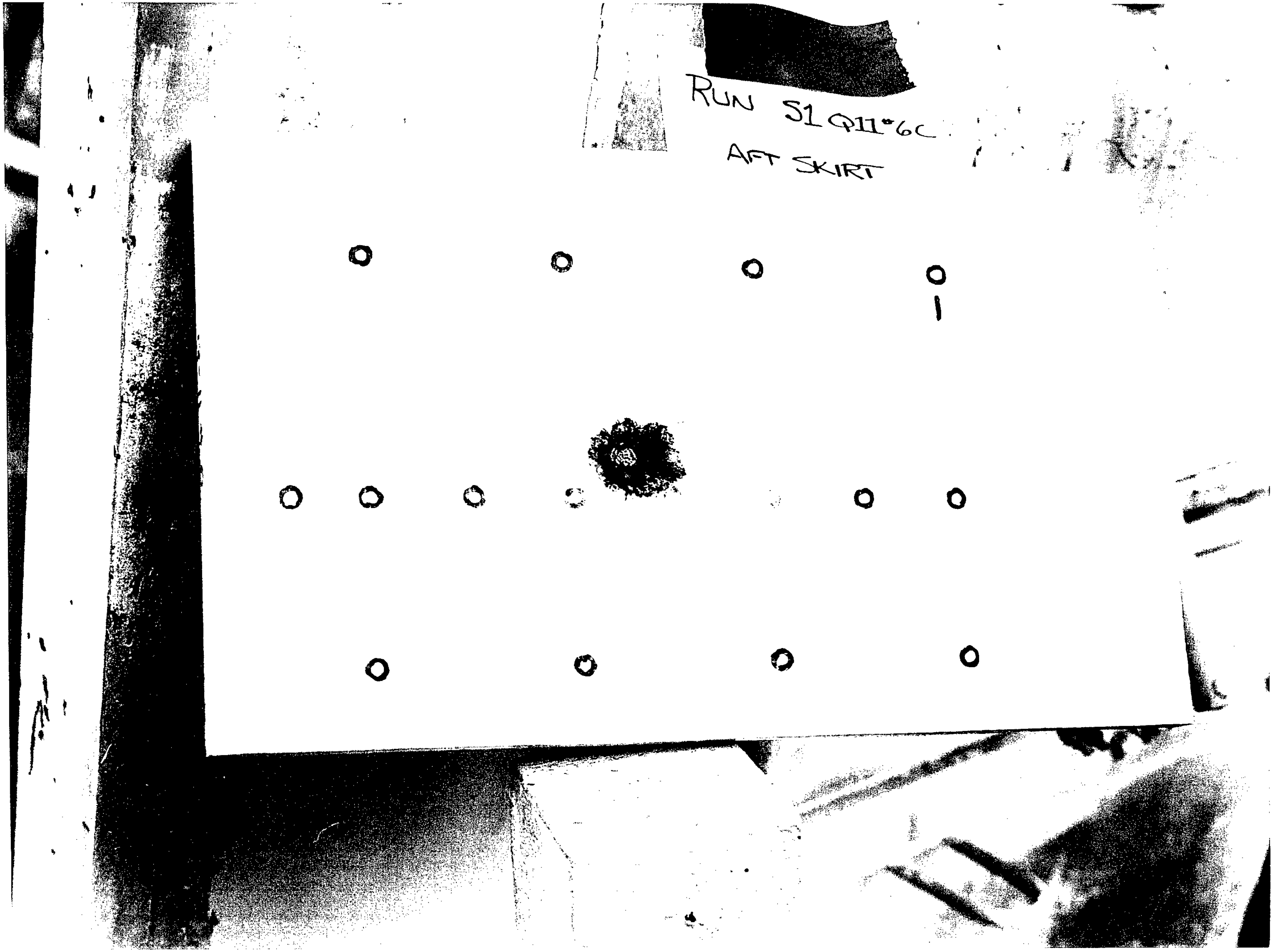


Figure B-46. Cumulative Damage Due to Components A, B, and C to Panel Q-11#6, Front View.

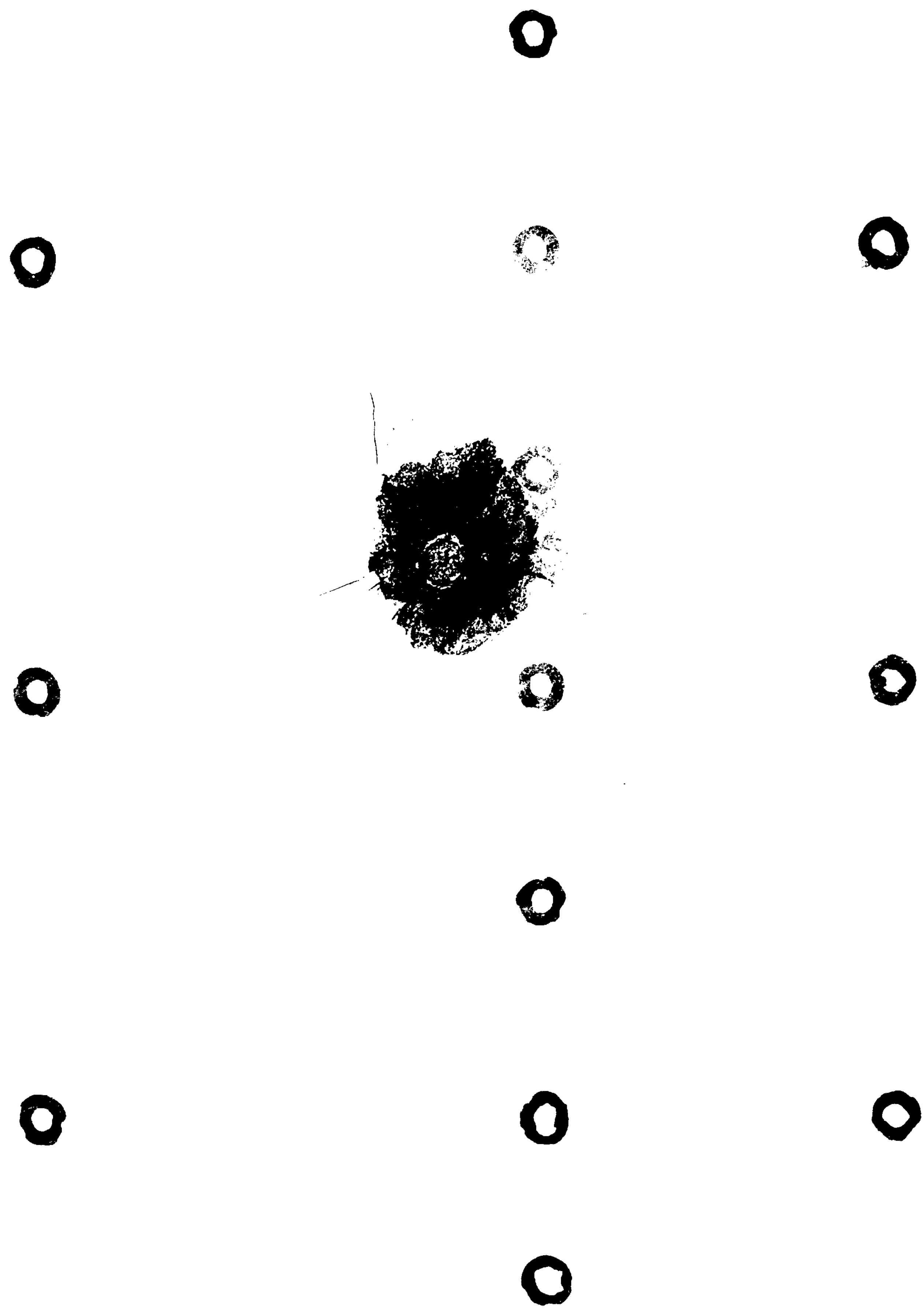


Figure B-47. Cumulative Damage Due to Components A, B, and C to Panel Q-11#6, Close Up View.

Figure B-48. Cumulative Damage Due to Components A, B, and C to Panel Q-11#6, Back View.

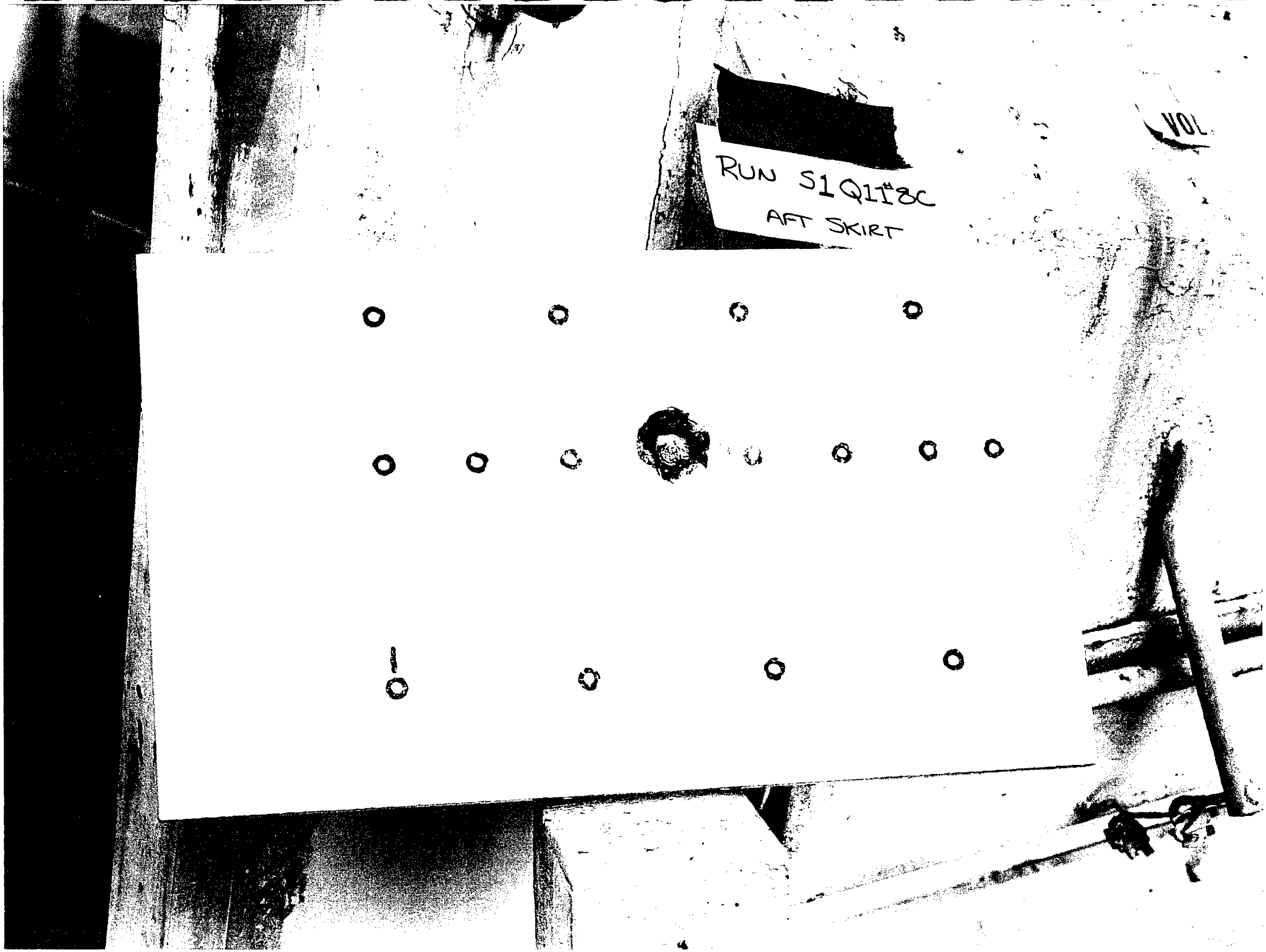


Figure B-49. Cumulative Damage Due to Components A, B, and C to Panel Q-11#8, Front View.

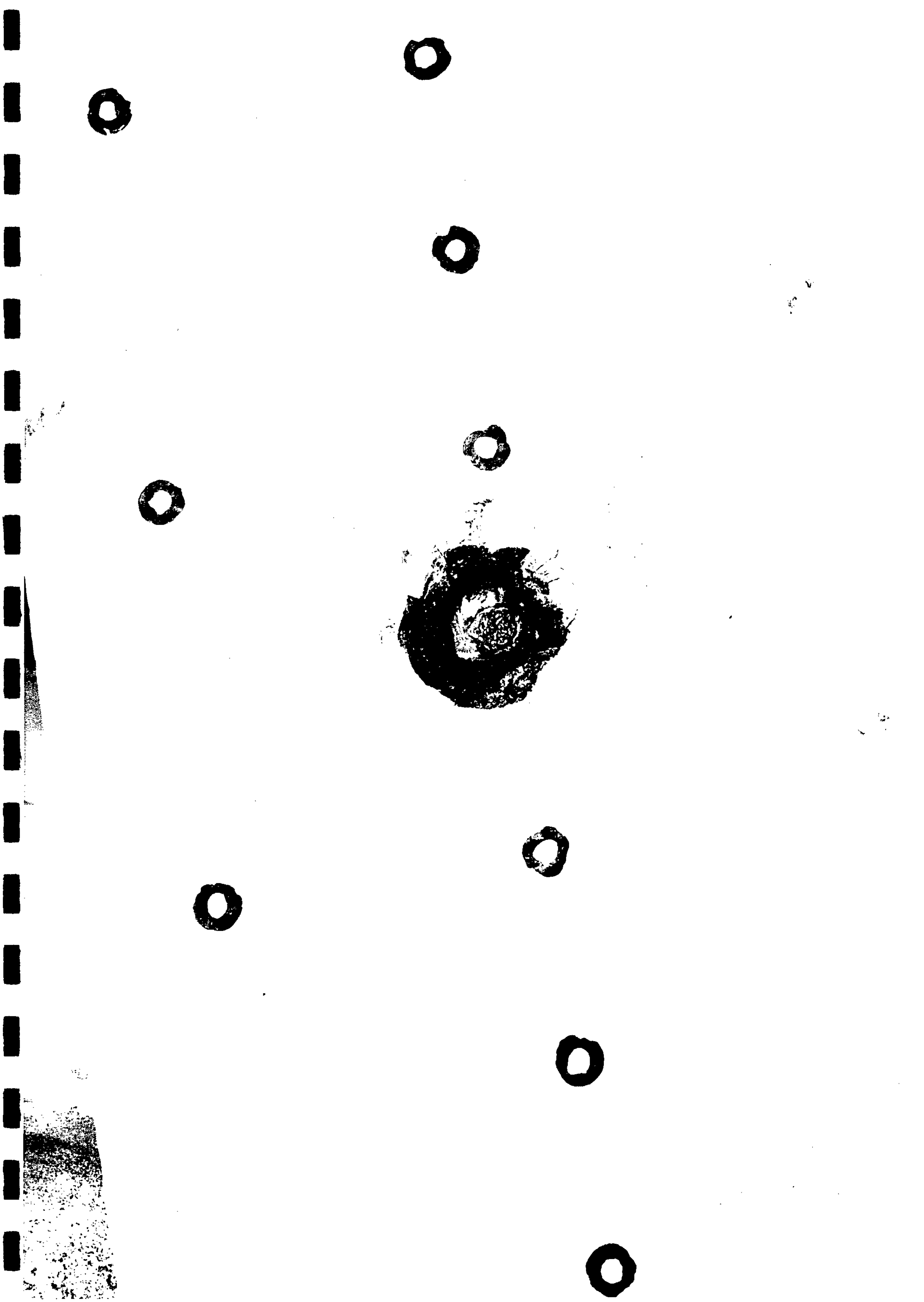


Figure B-50. Cumulative Damage Due to Components A, B, and C to Panel Q-11#8, Close Up View.

Figure B-51. Cumulative Damage Due to Components A, B, and C to Panel Q-11#8, Back View.

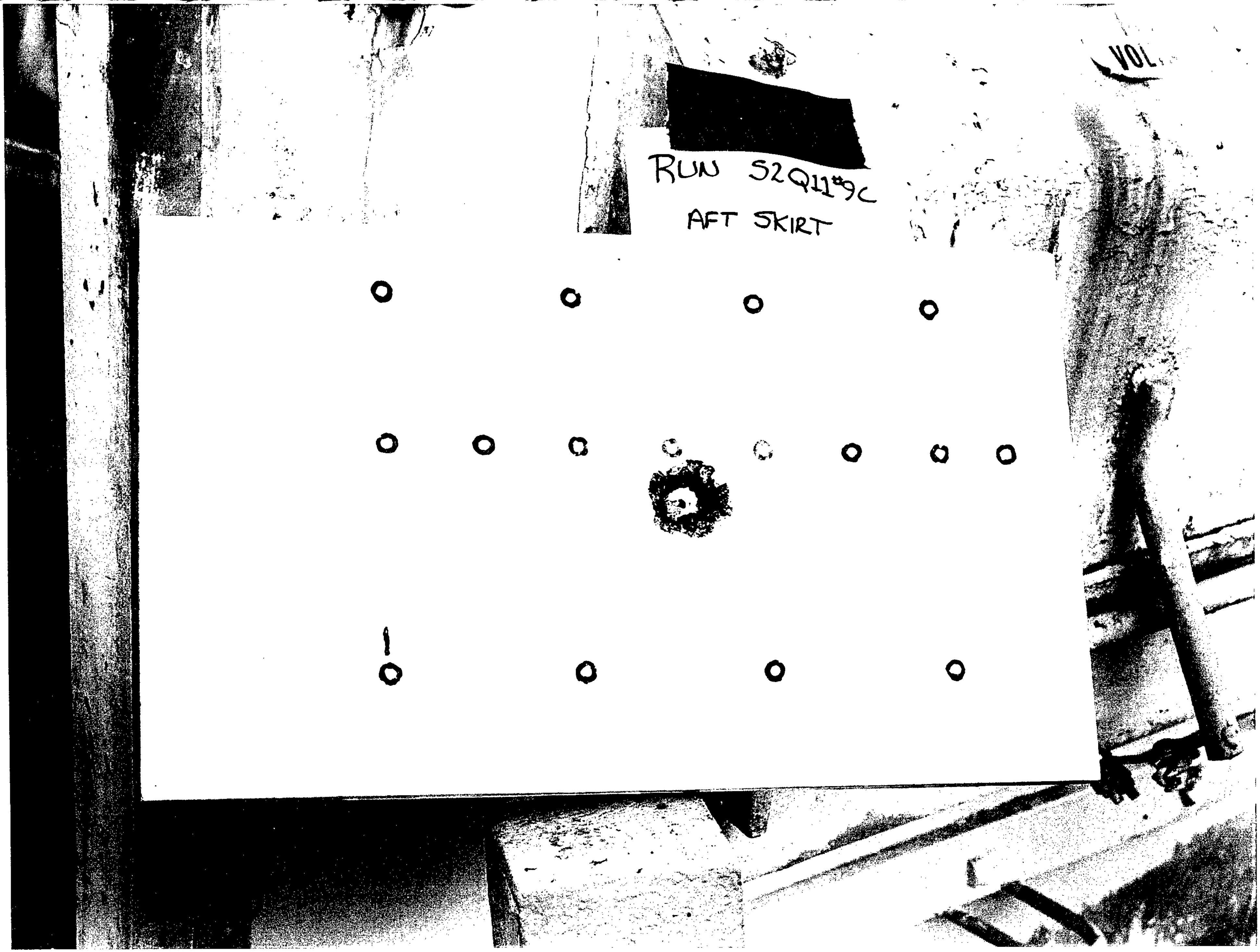


Figure B-52. Cumulative Damage Due to Components A, B, and C to Panel Q-11#9, Front View.

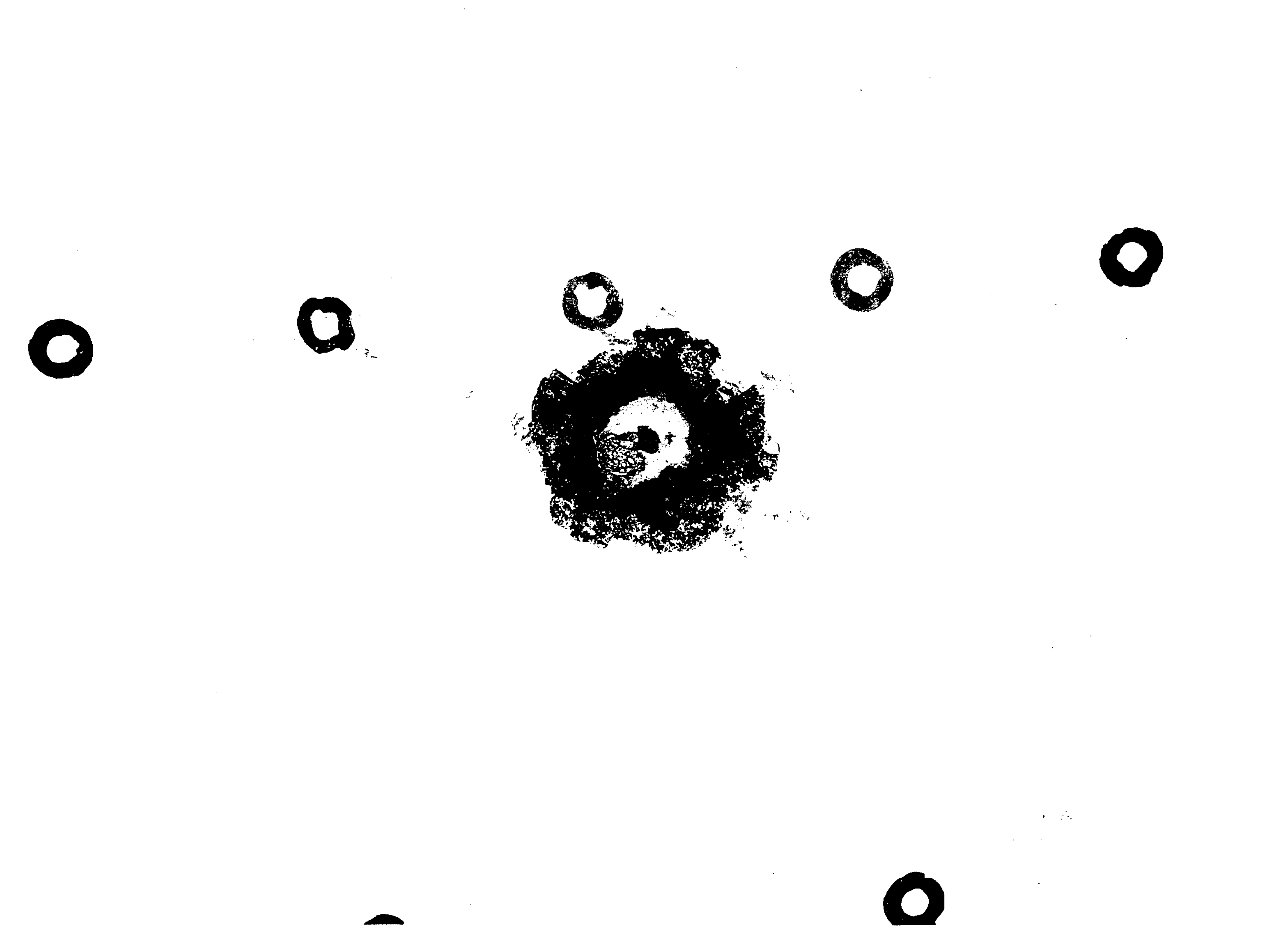


Figure B-53. Cumulative Damage Due to Components A, B, and C to Panel Q-11#9, Close Up View.

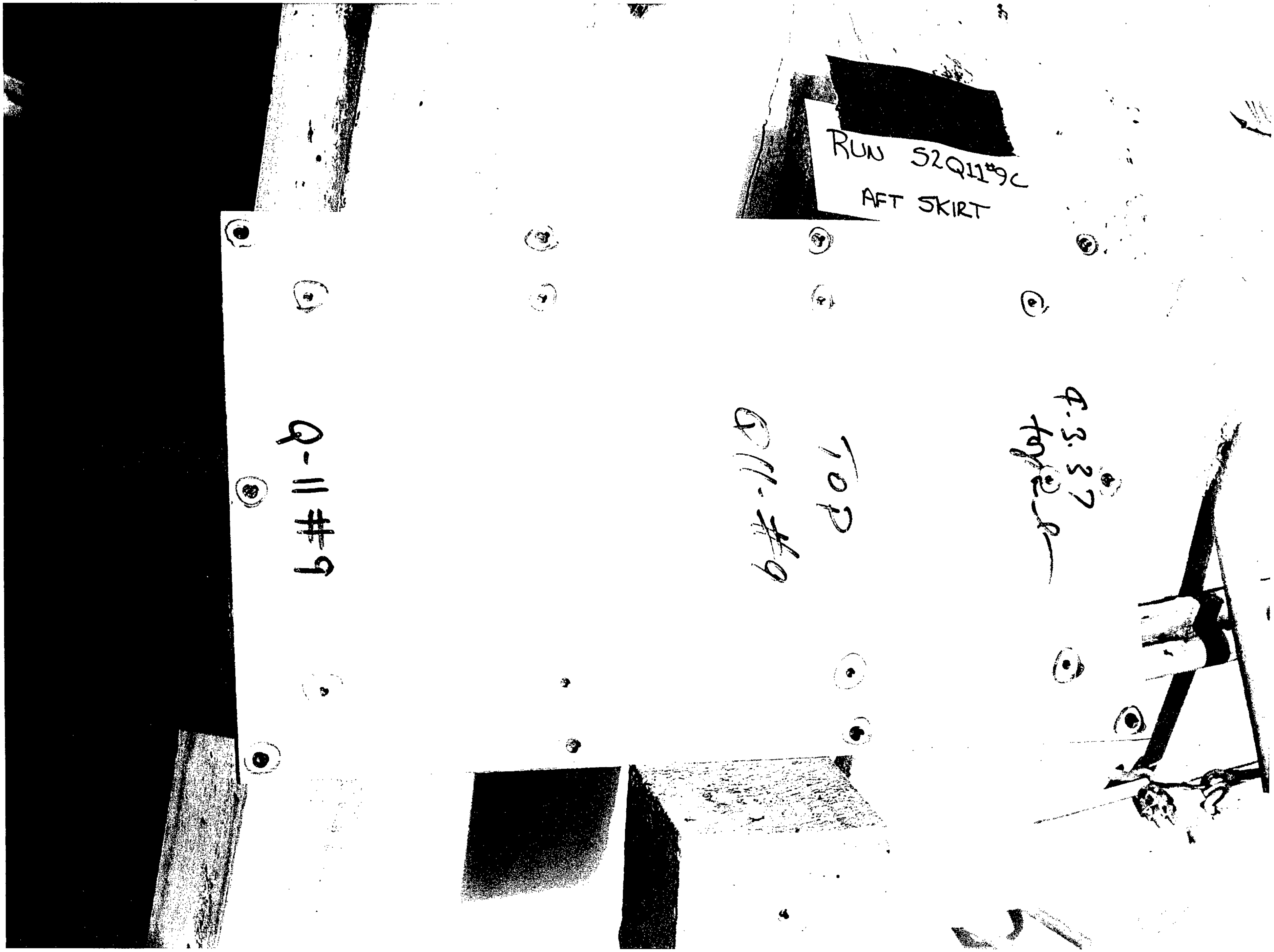


Figure B-54. Cumulative Damage Due to Components A, B, and C to Panel Q-11#9, Back View.

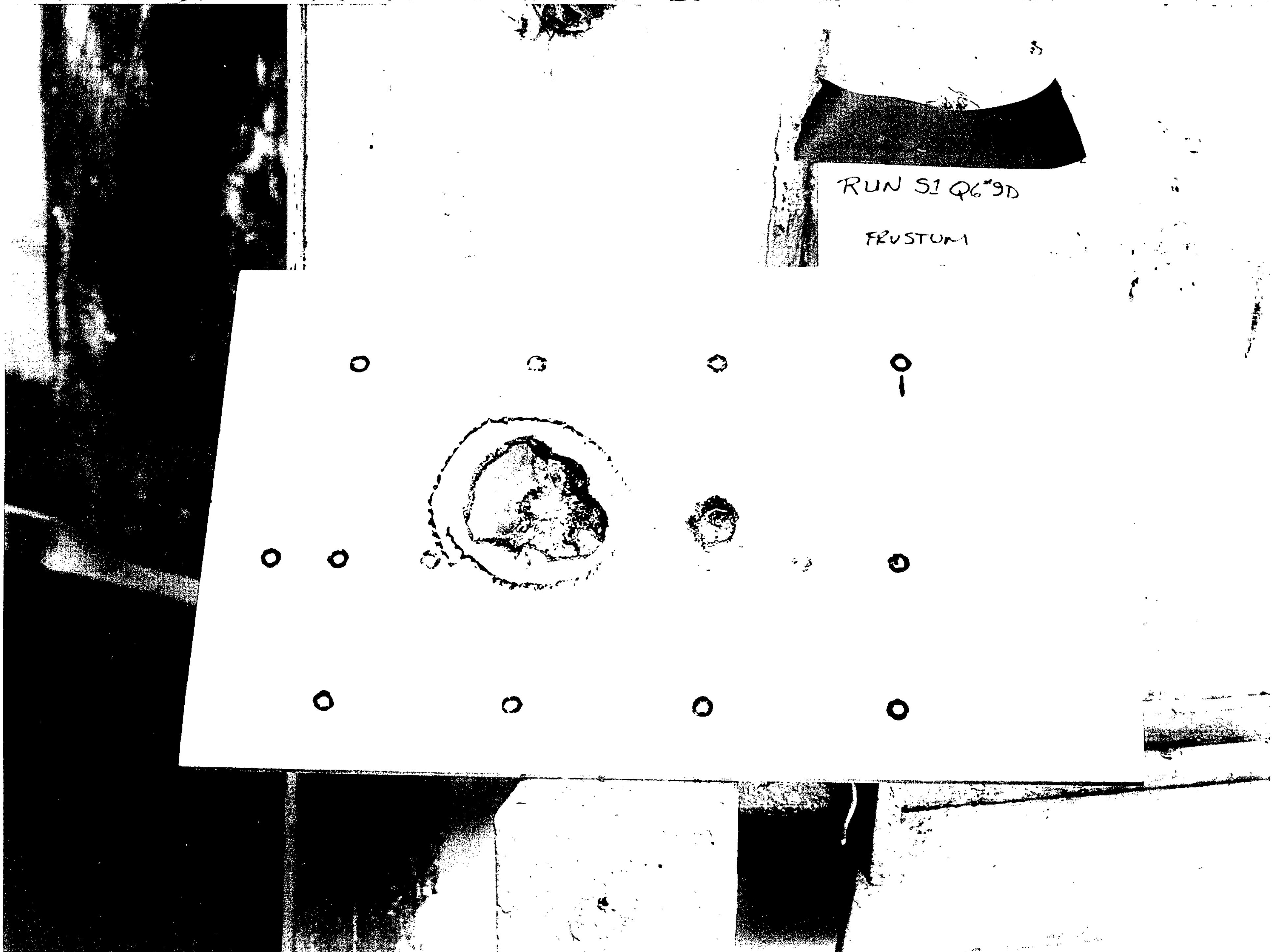


Figure B-55. Cumulative Damage Due to Components A, B, C, and D to Panel Q-6#9, Front View.

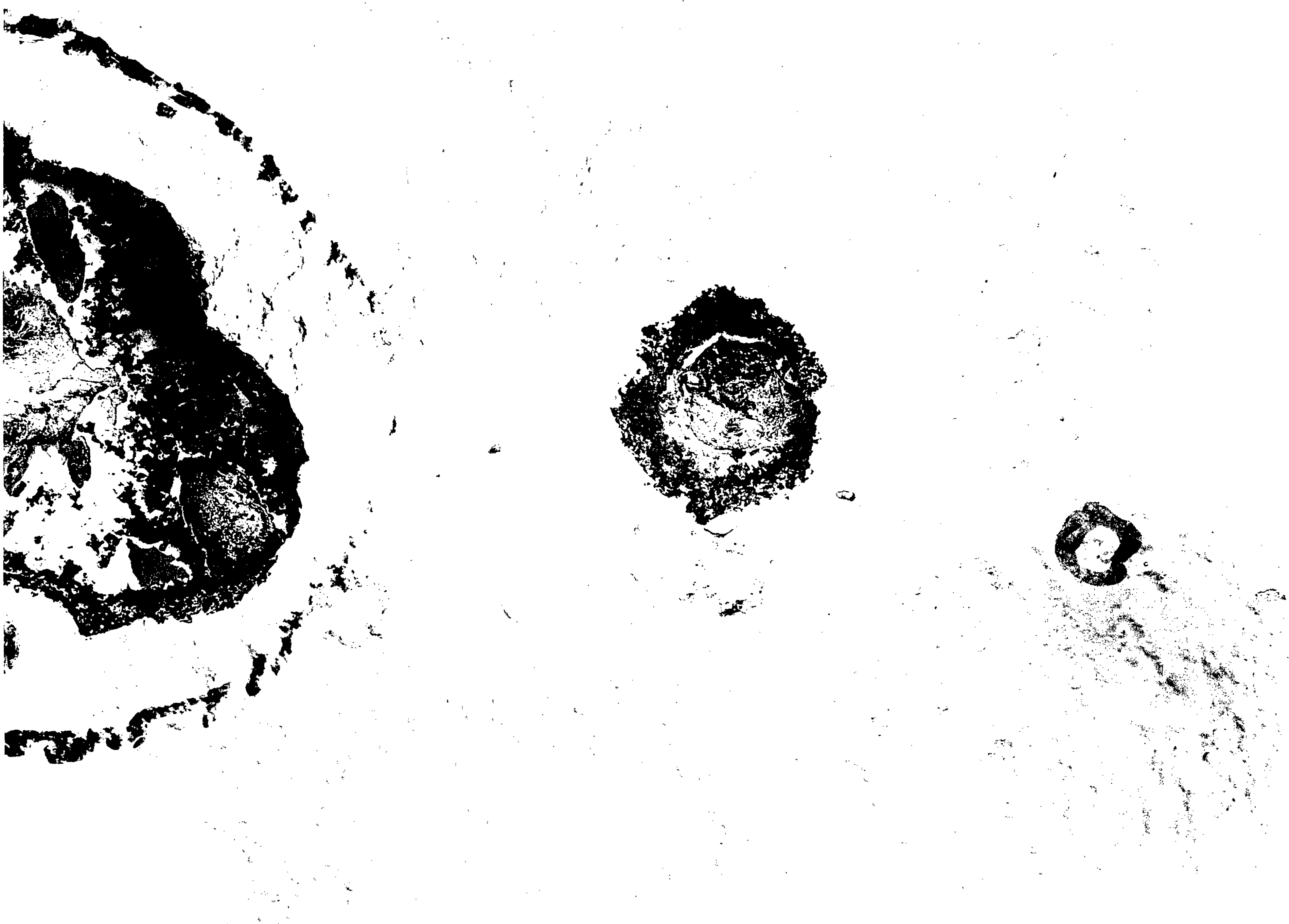


Figure B-56. Cumulative Damage Due to Components A, B, C, and D to Panel Q-6#9. Close Up View.

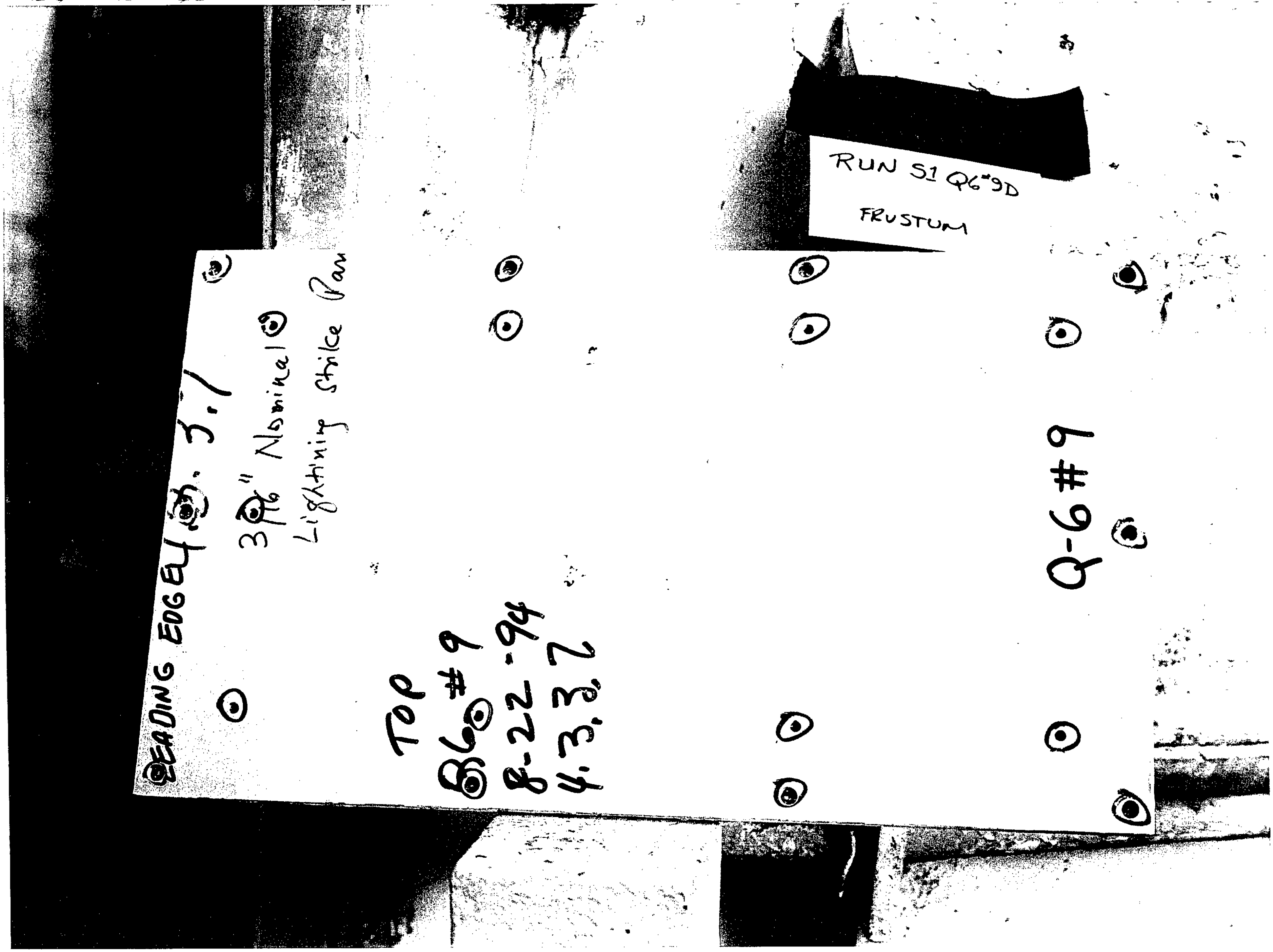


Figure B-57. Cumulative Damage Due to Components A, B, C, and D to Panel Q-6#9, Back View.

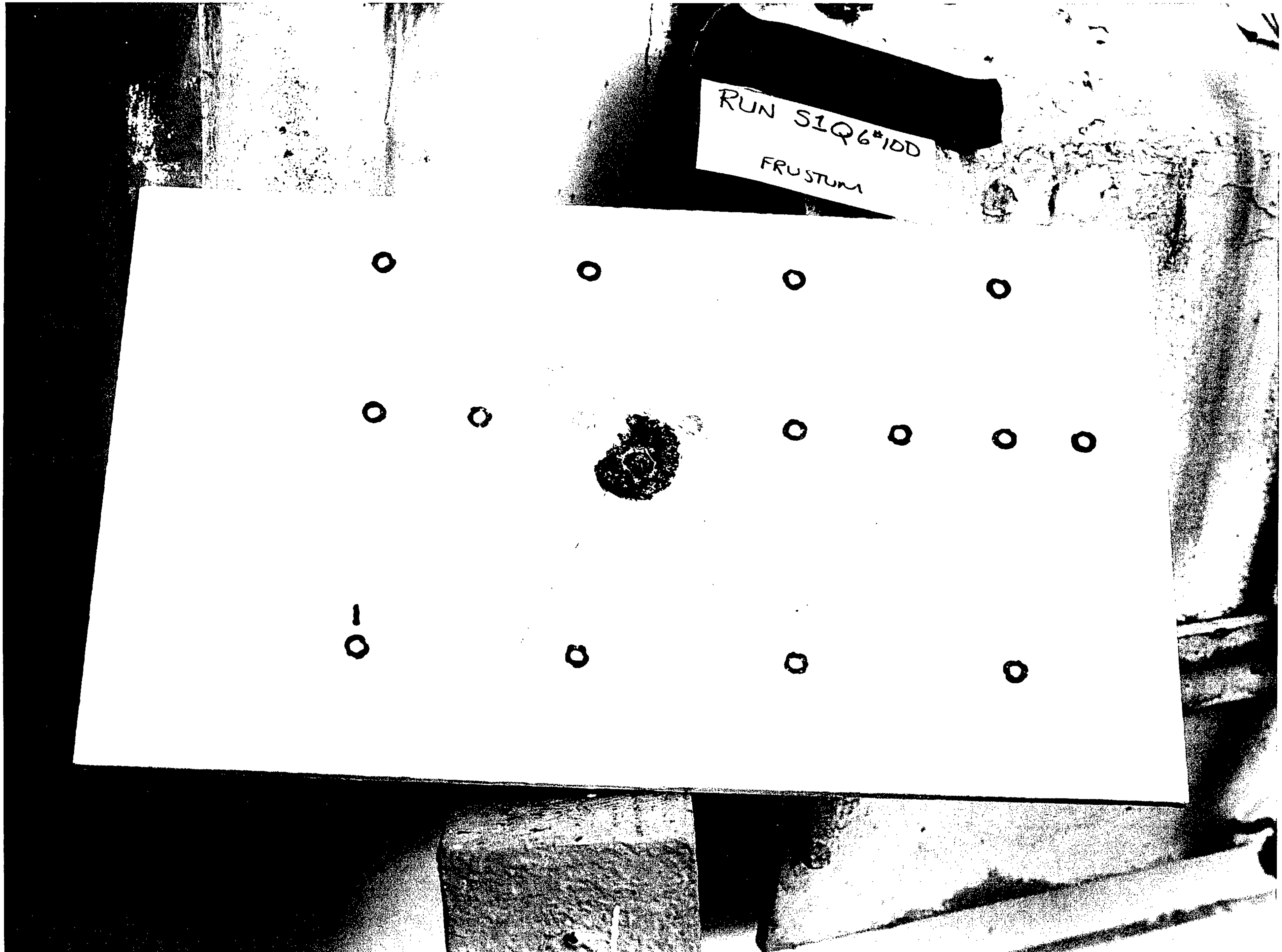


Figure B-58. Cumulative Damage Due to Components A, B, C, and D to Panel Q-6#10, Front View.

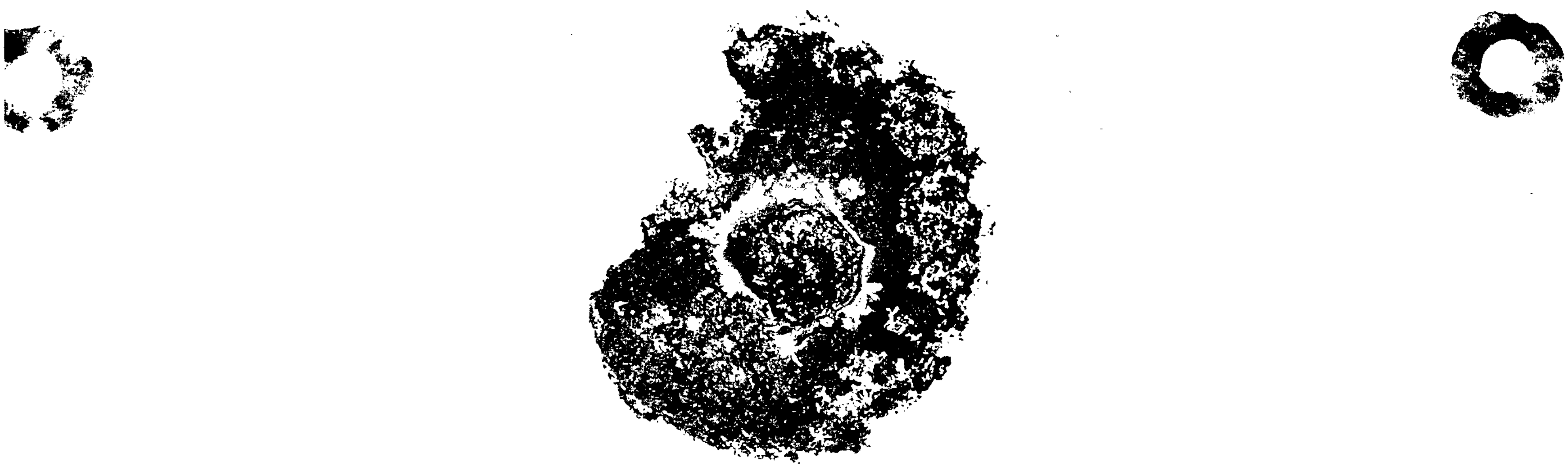


Figure B-59. Cumulative Damage Due to Components A, B, C, and D to Panel Q-6#10, Close Up View.

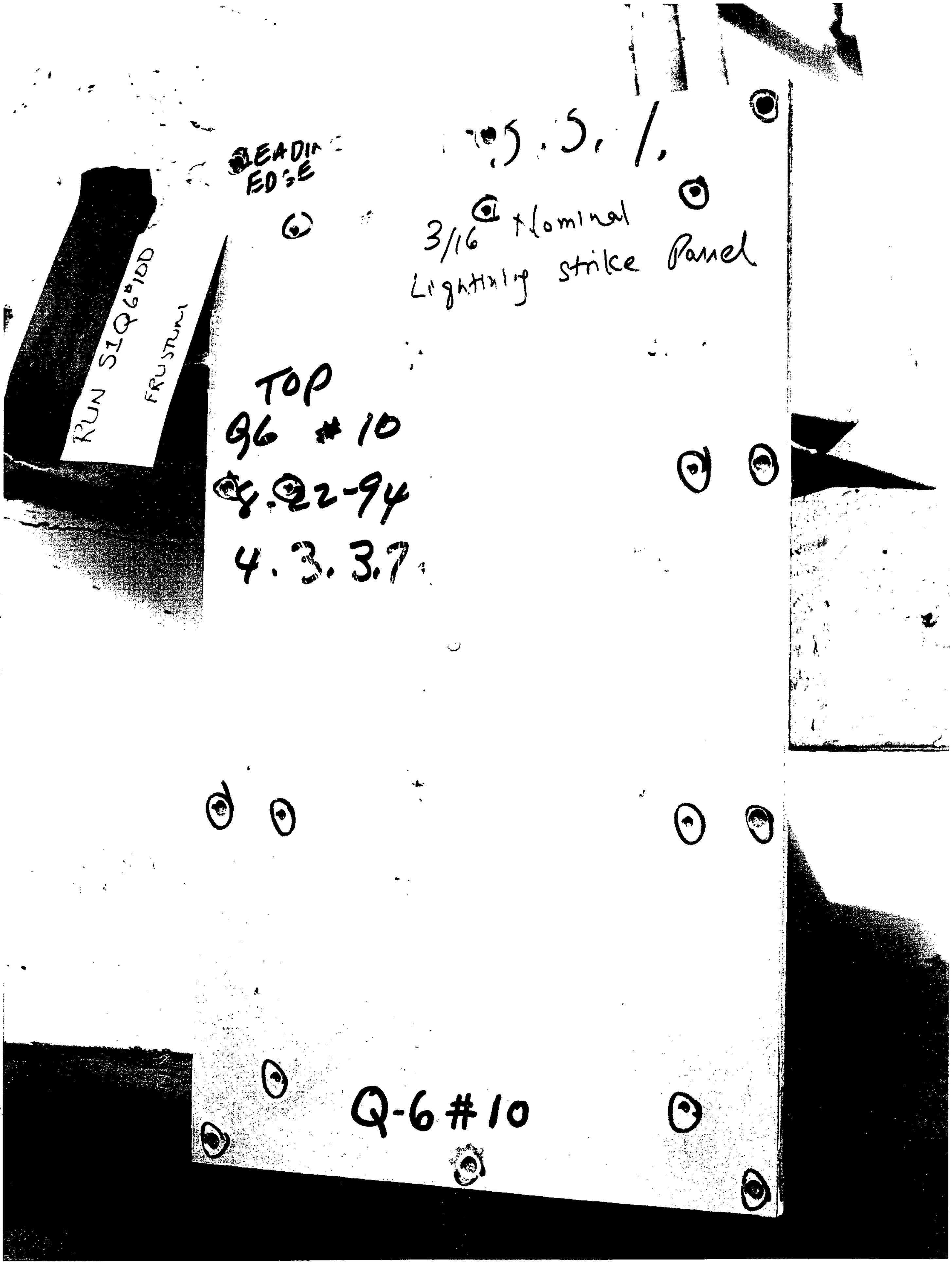


Figure B-60. Cumulative Damage Due to Components A, B, C, and D to Panel Q-6#10, Back View.

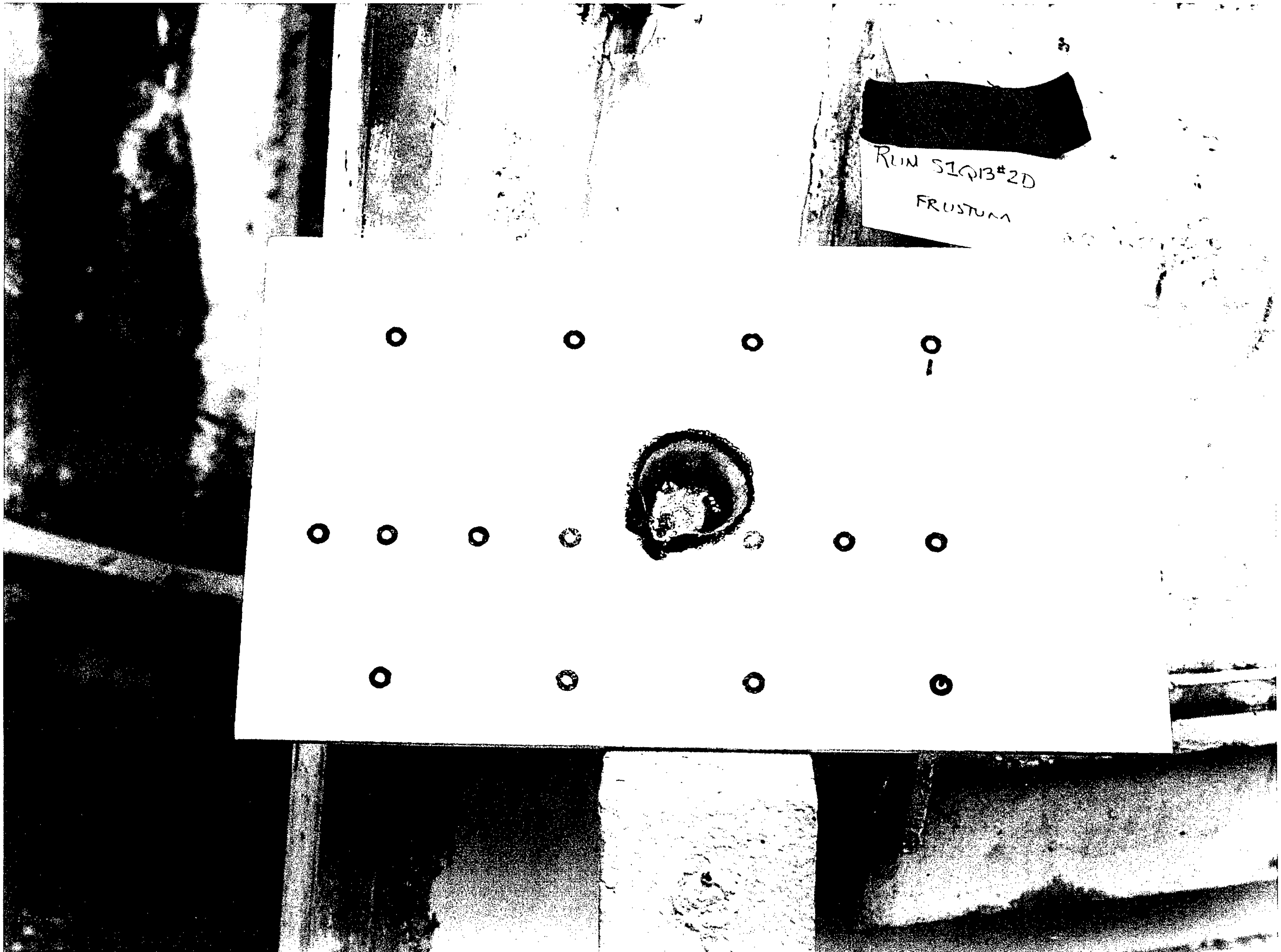


Figure B-61. Cumulative Damage Due to Components A, B, C, and D to Panel Q-13#2, Front View.

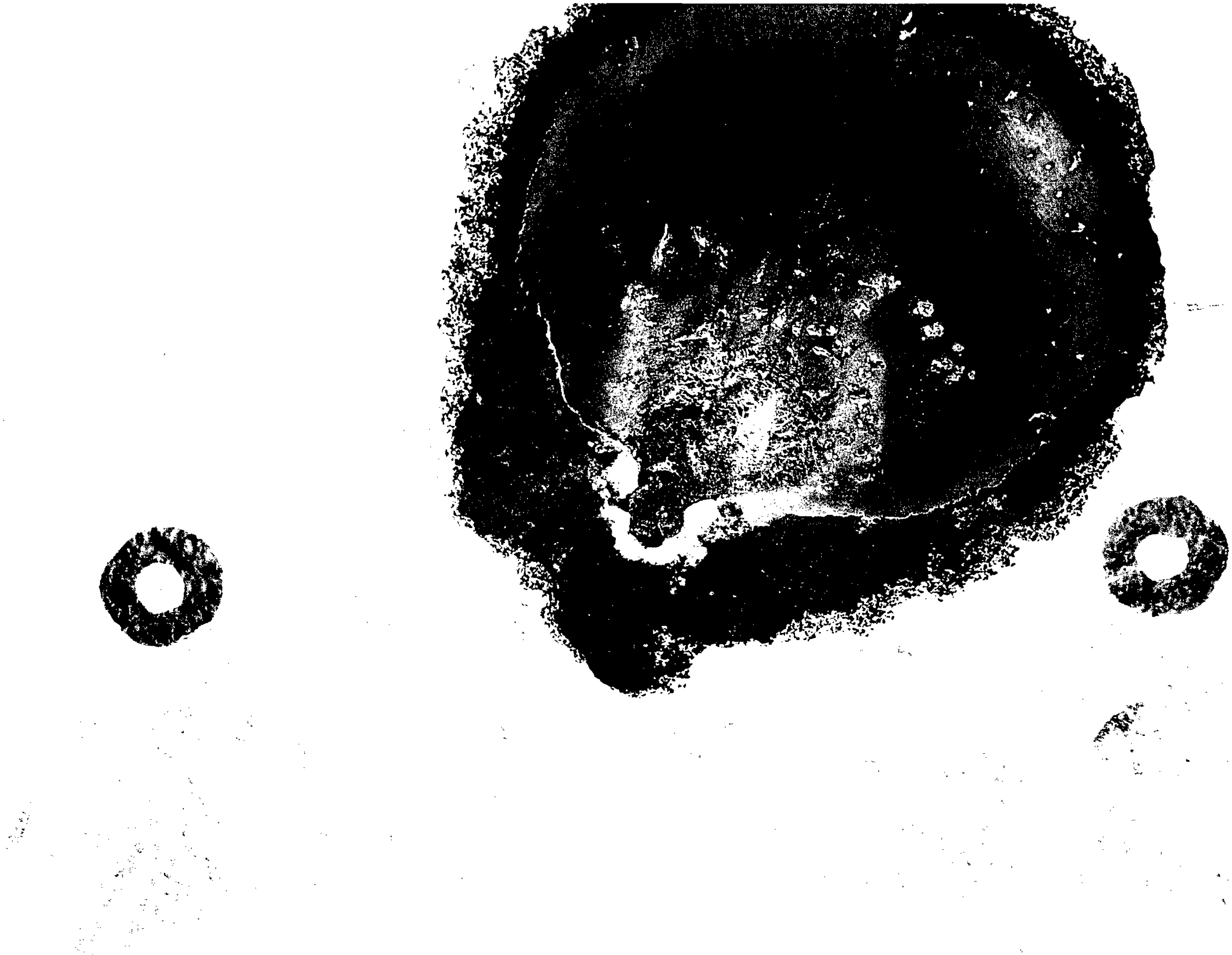


Figure B-62. Cumulative Damage Due to Components A, B, C, and D to Panel Q-13#2, Close Up View.

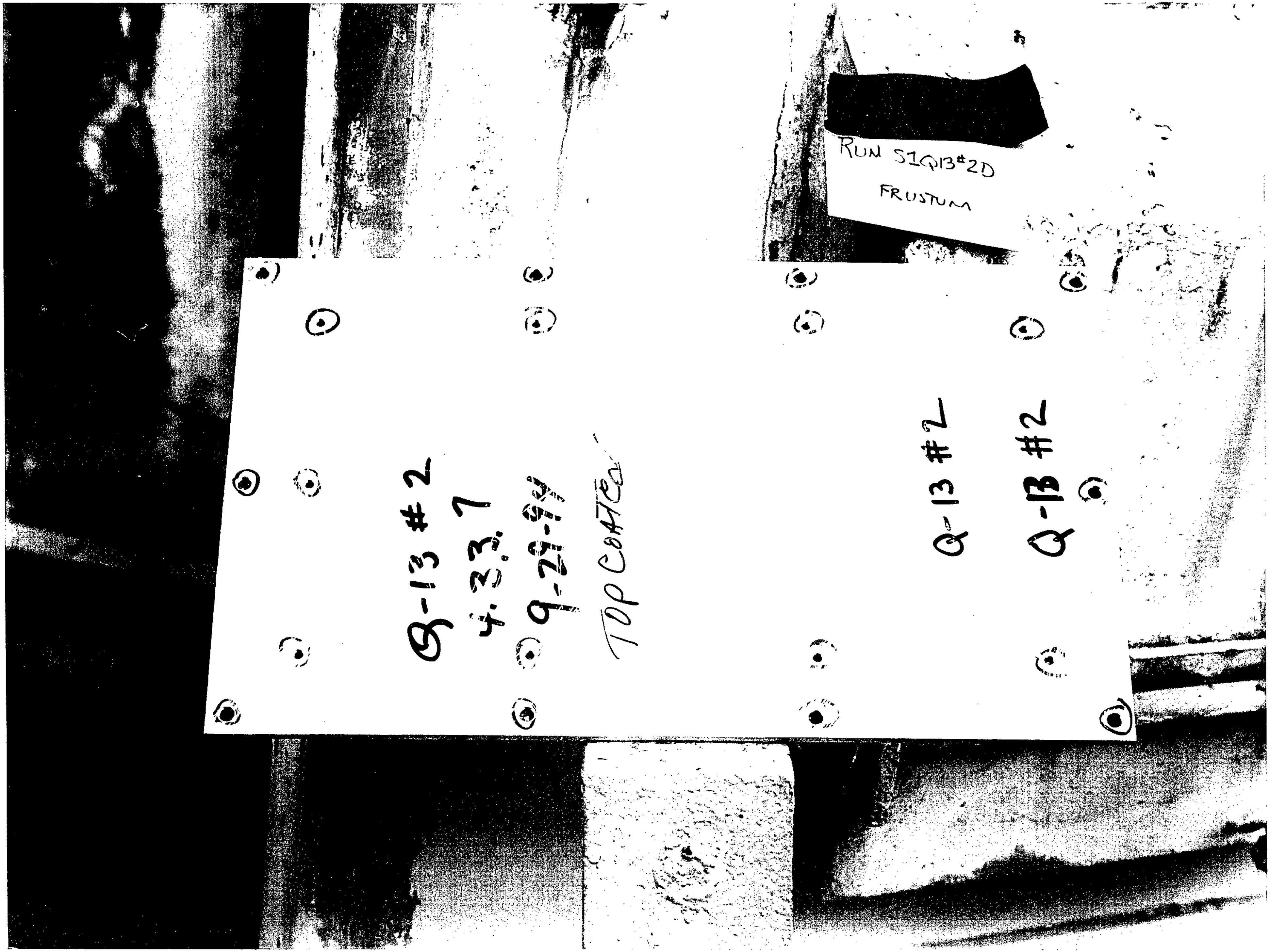


Figure B-63. Cumulative Damage Due to Components A, B, C, and D to Panel Q-13#2, Back View.

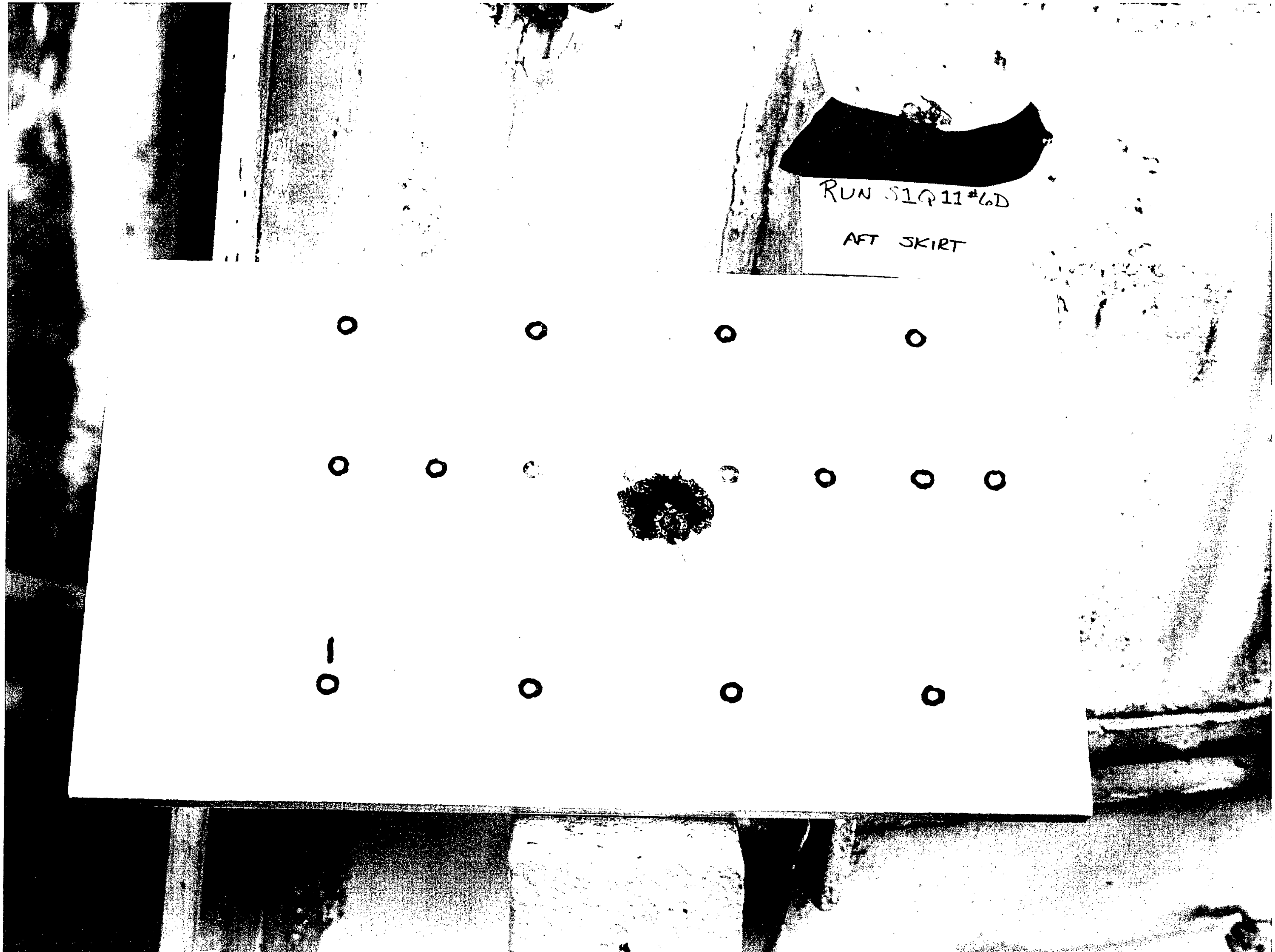


Figure B-64. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#6, Front View.

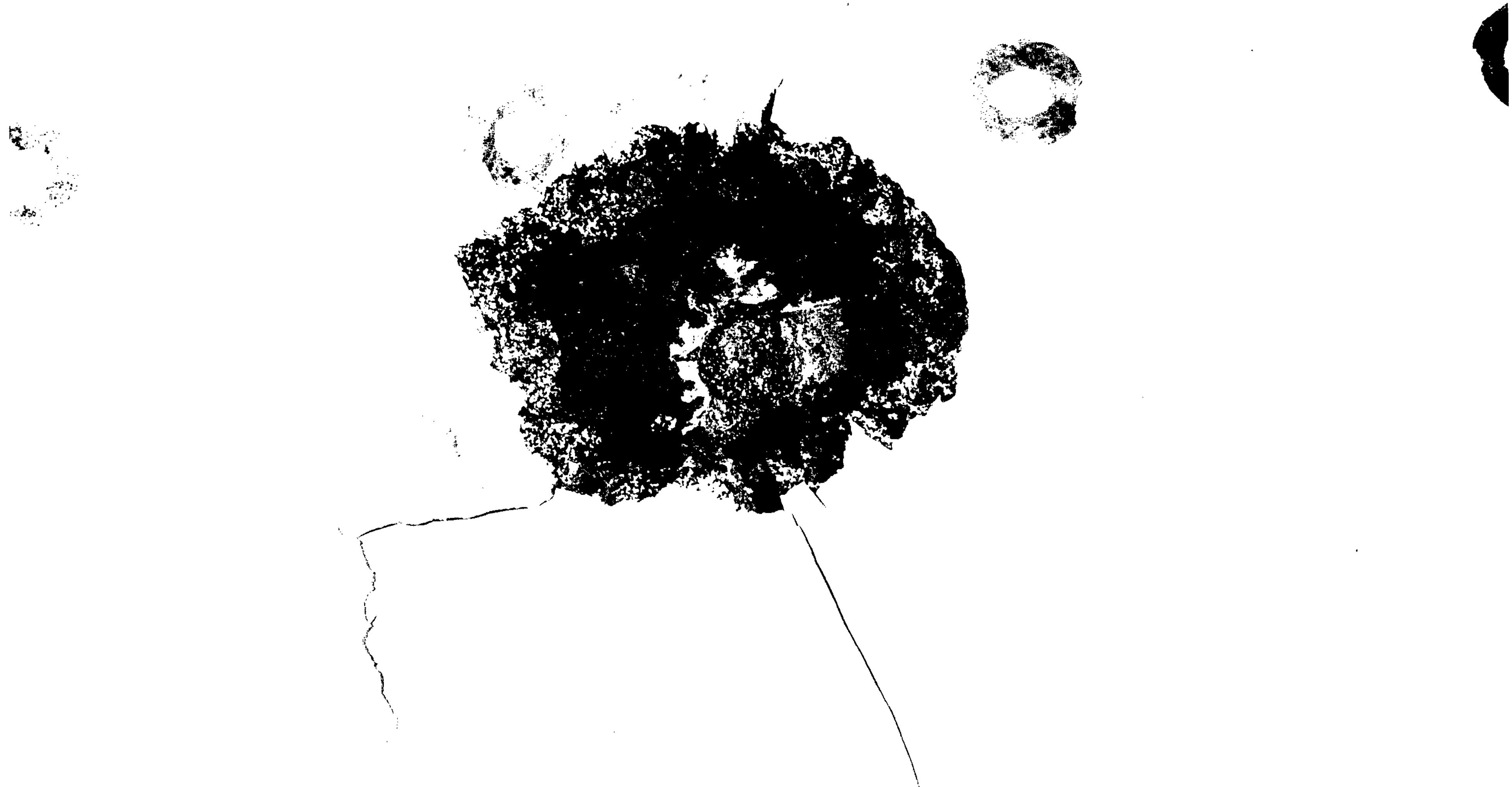


Figure B-65. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#6, Close Up View.

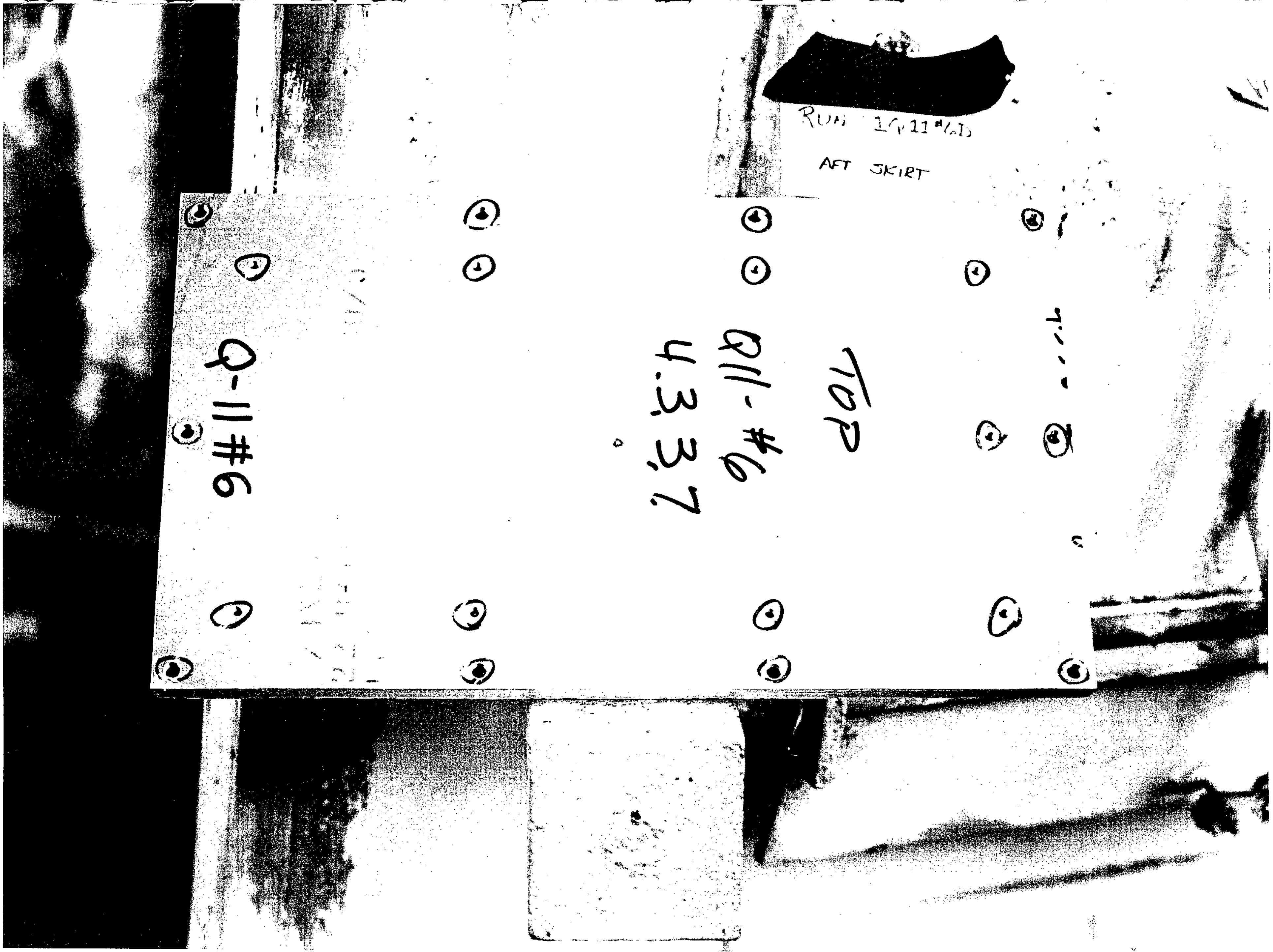


Figure B-66. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#6, Back View.

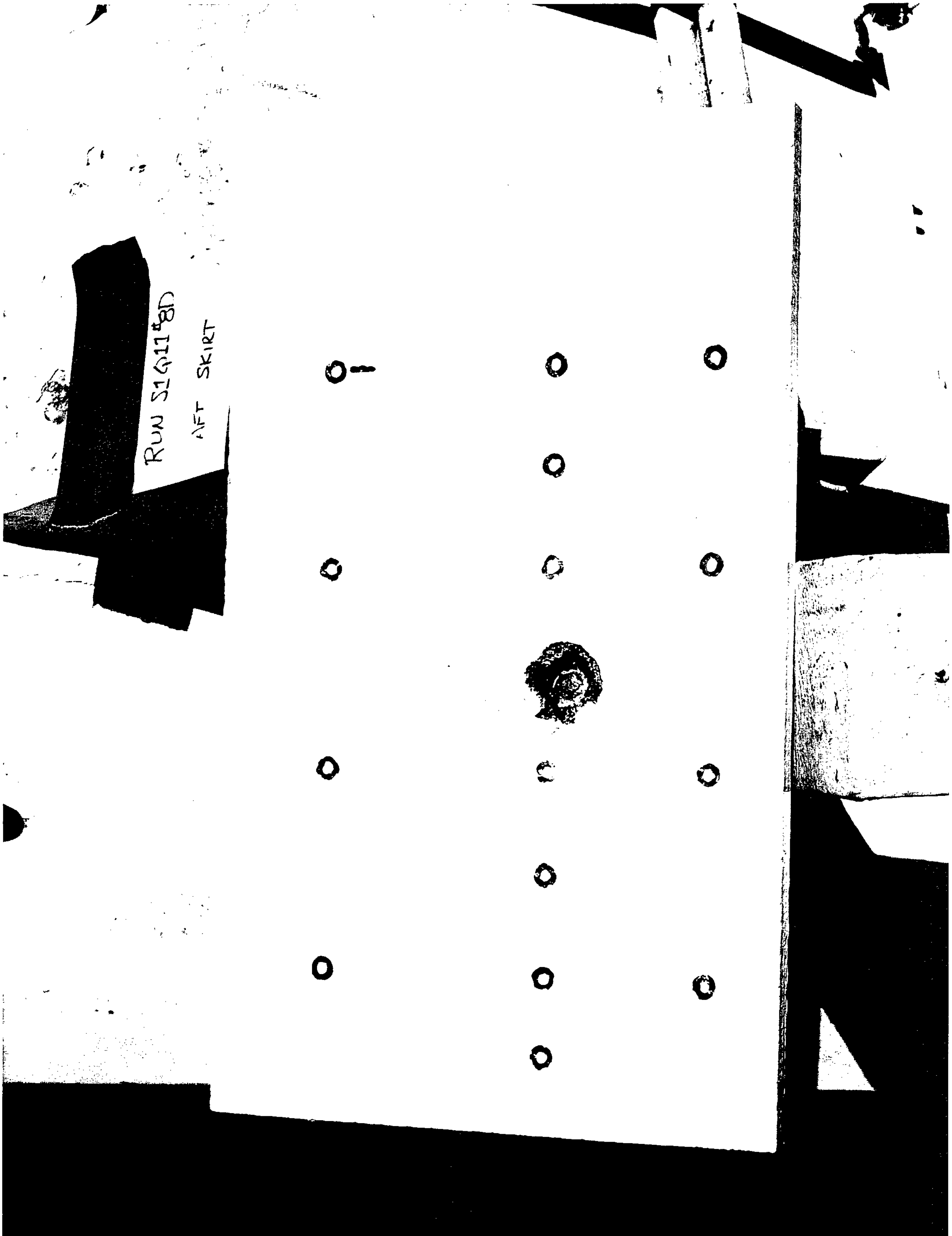


Figure B-67. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#8, Front View.

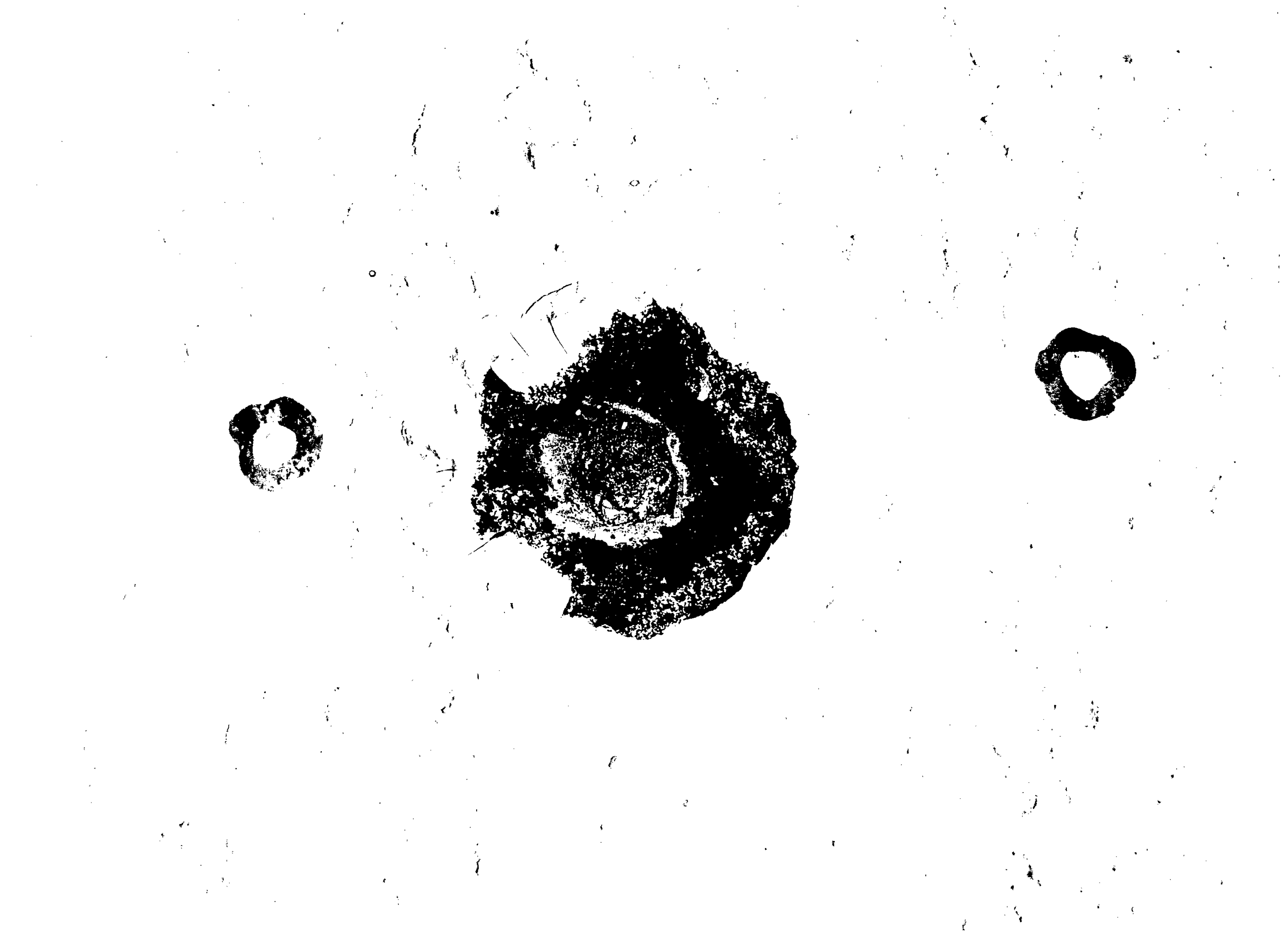


Figure B-68. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#8, Close Up View.

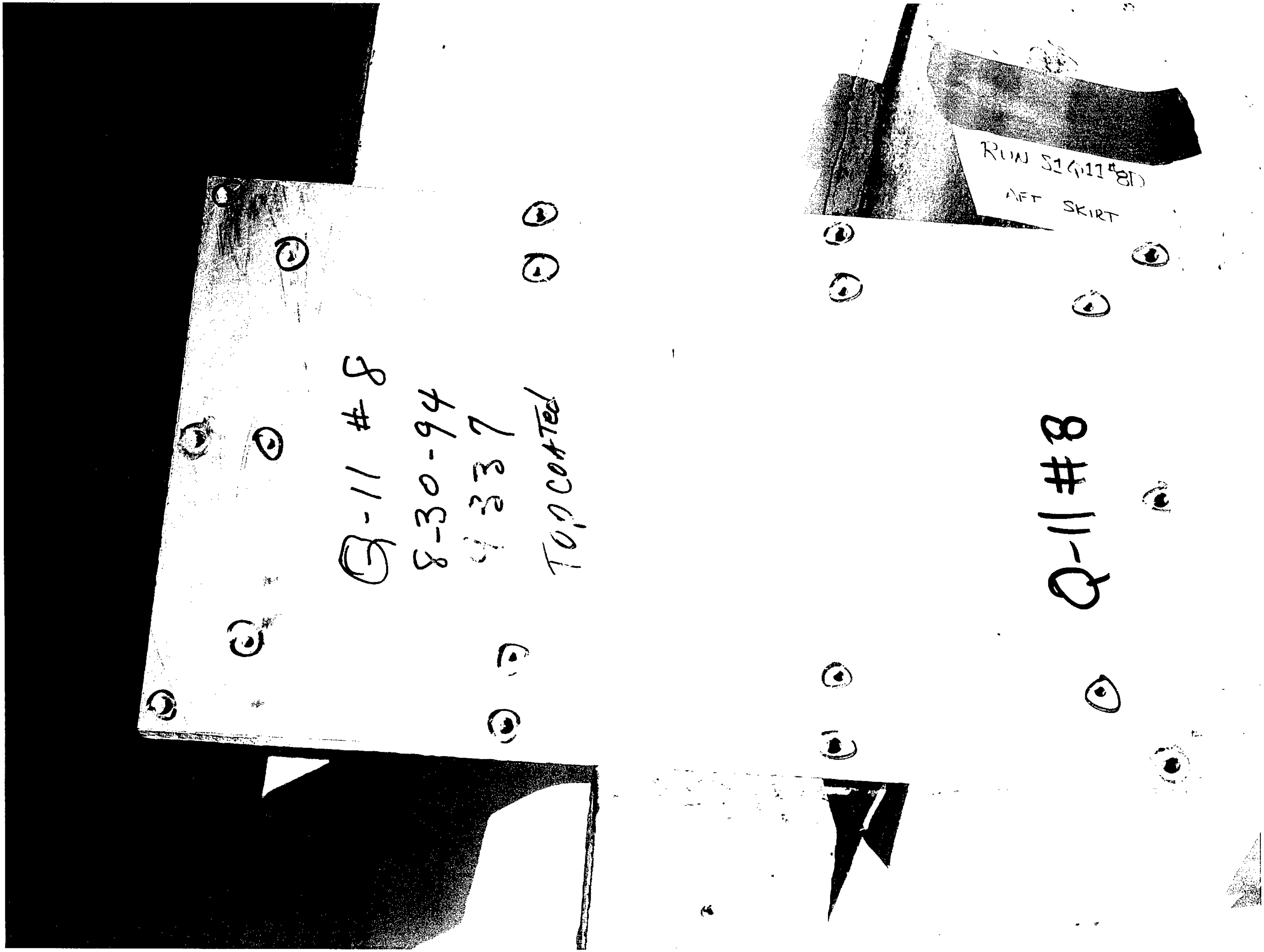


Figure B-69. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#8. Back View.

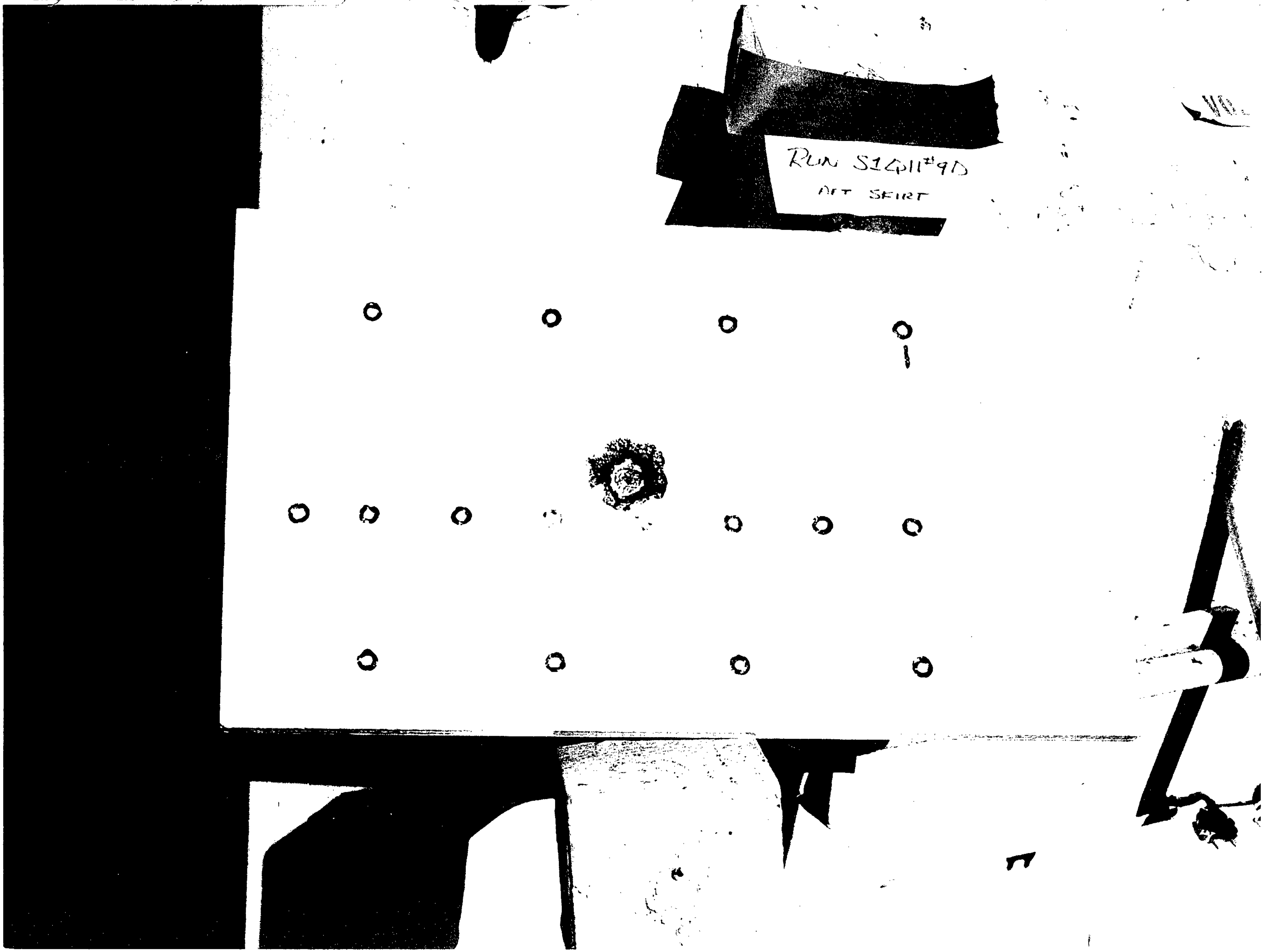


Figure B-70. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#9, Front View.

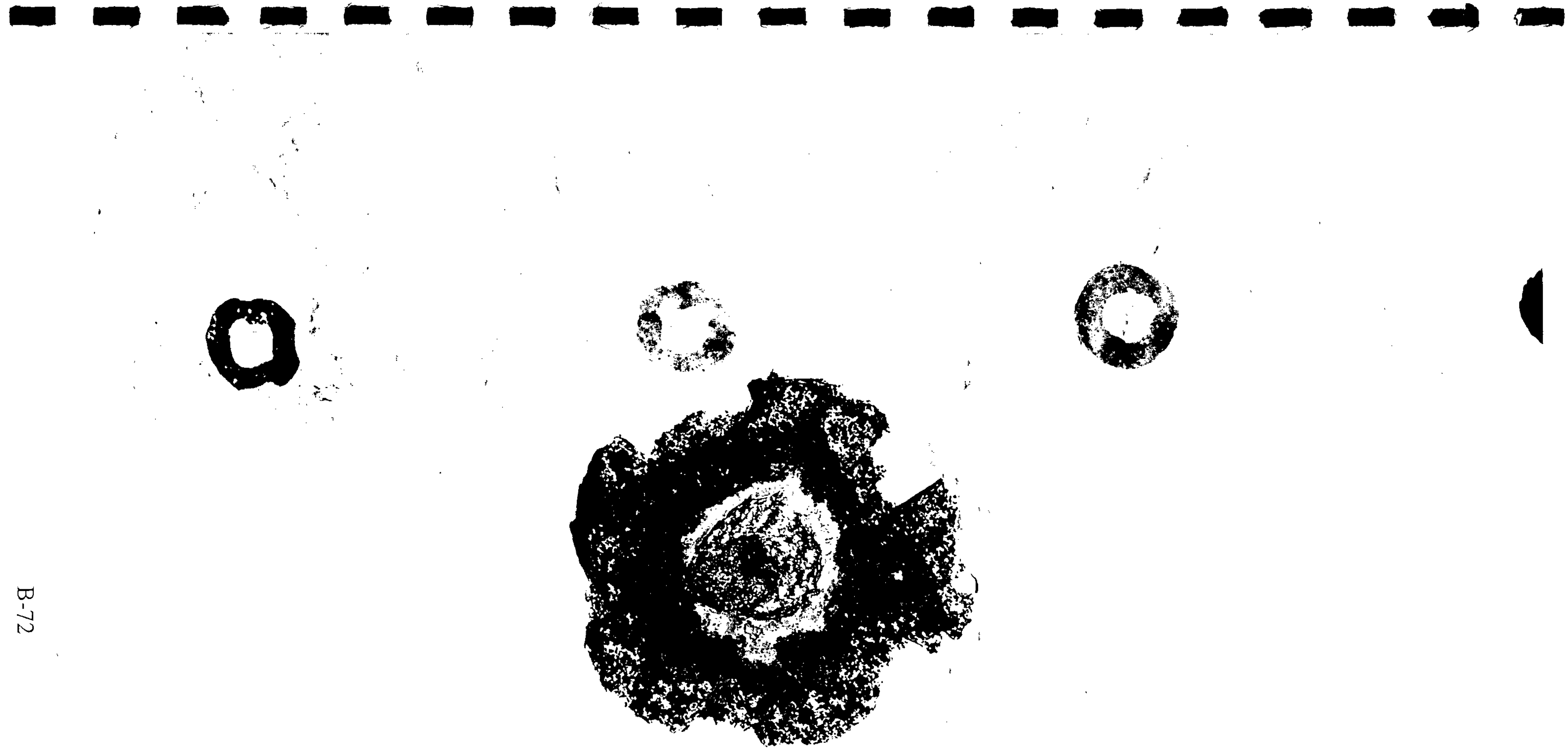


Figure B-71. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#9, Close Up View.

Figure B-72. Cumulative Damage Due to Components A, B, C, and D to Panel Q-11#9, Back View.

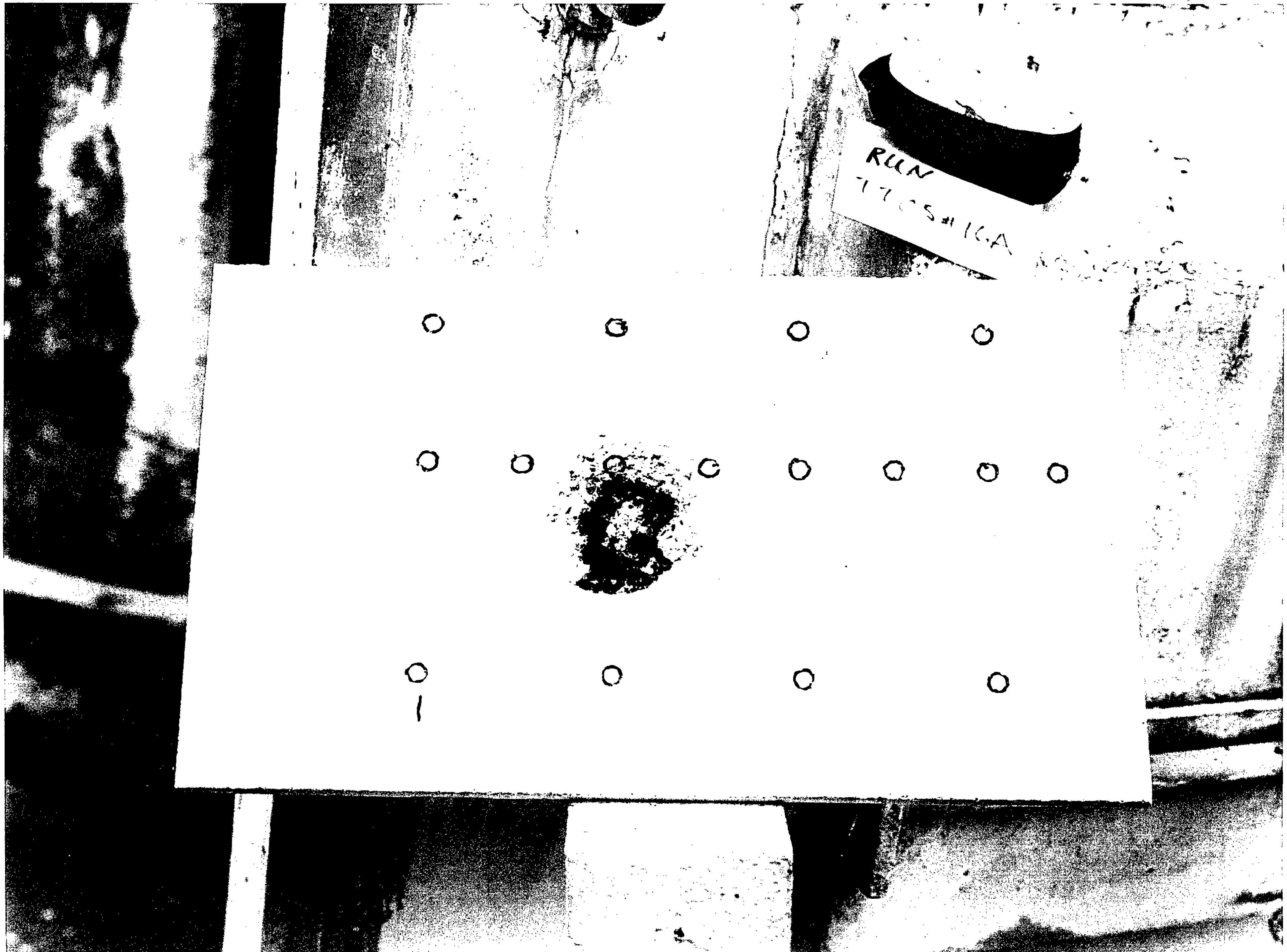


Figure B-73. Resultant Damage Due to Component A to Panel TTC5#16, Front View (No Gap).

Figure B-74. Resultant Damage Due to Component A to Panel TTC5#16. Close Up View (No Gap).

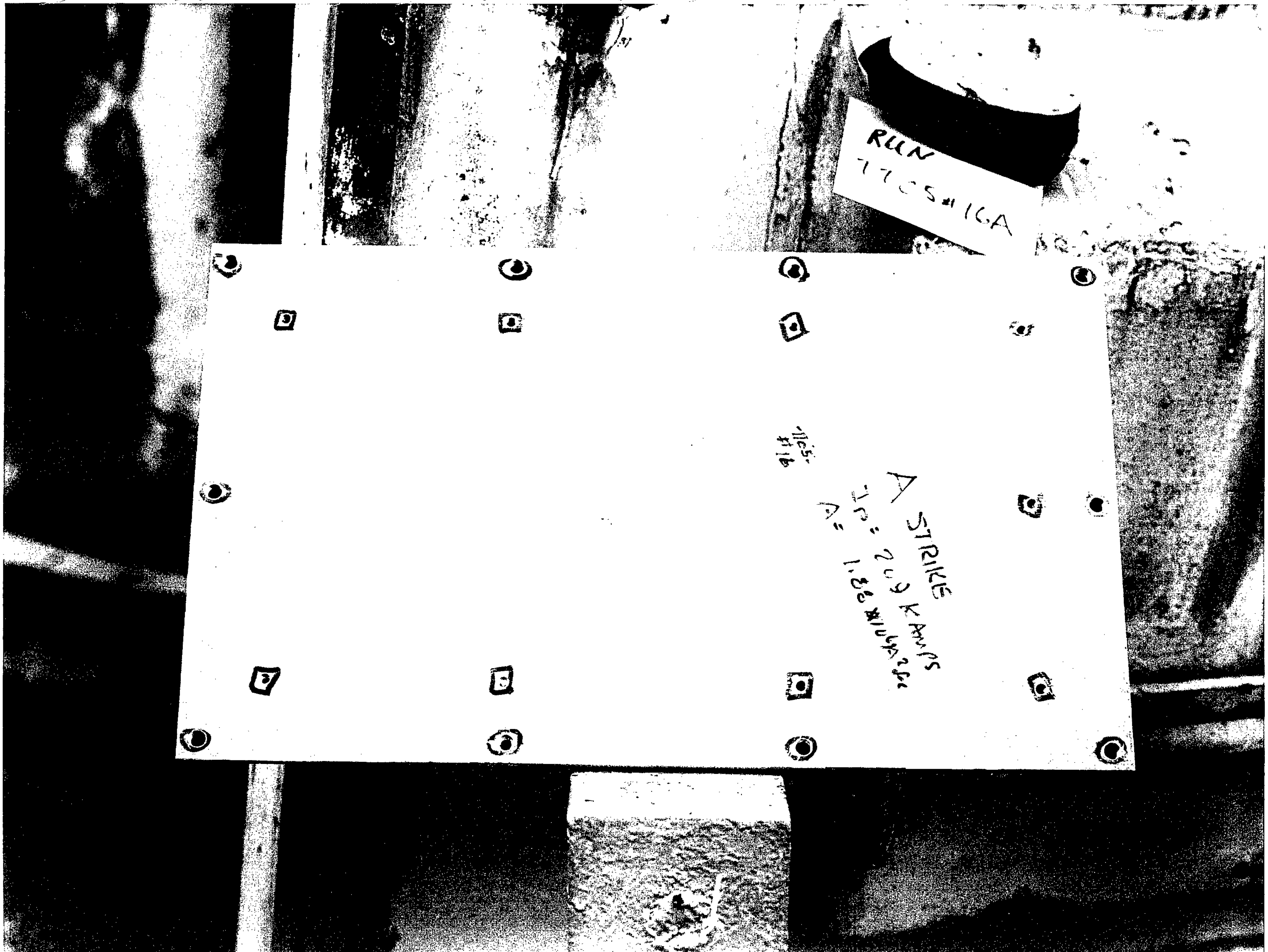


Figure B-75. Resultant Damage Due to Component A to Panel TTC5#16, Back View (No Gap).

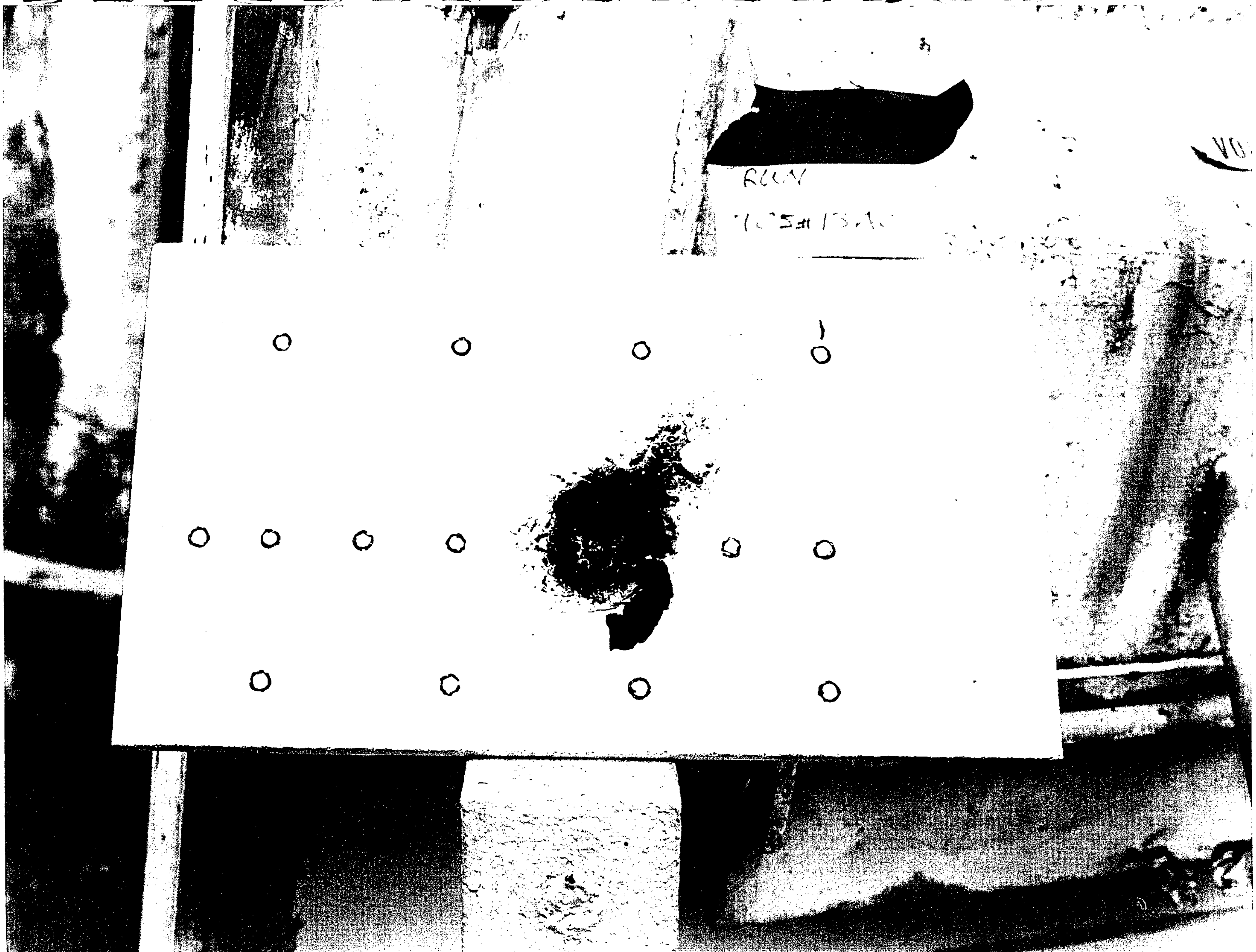


Figure B-76. Cumulative Damage Due to Simultaneous Components A and B to Panel TTC5#13. Front View.

Figure B-77. Cumulative Damage Due to Simultaneous Components A and B to Panel TTC5#13. Close Up View.

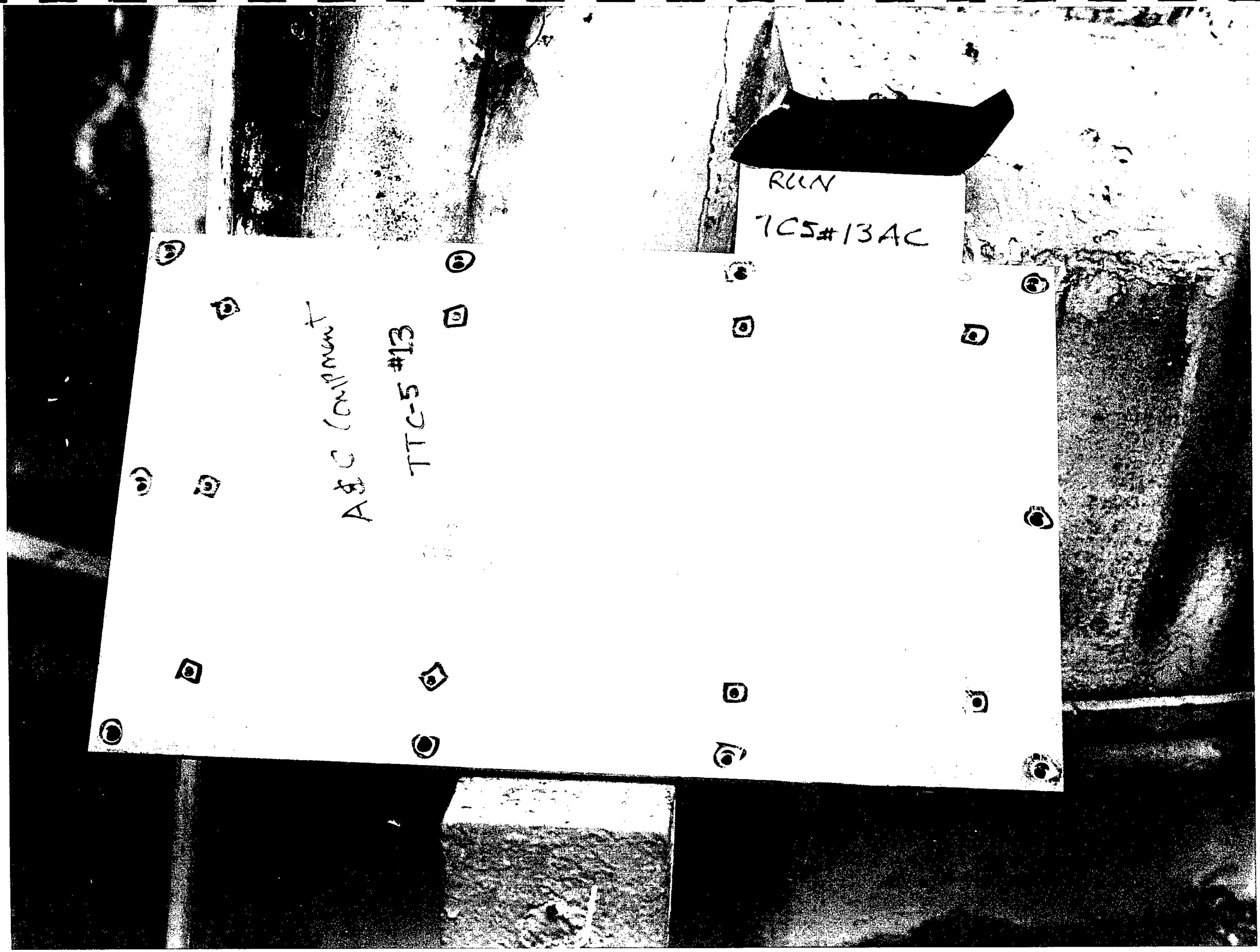


Figure B-78. Cumulative Damage Due to Simultaneous Components A and B to Panel TTC5#13, Back View.

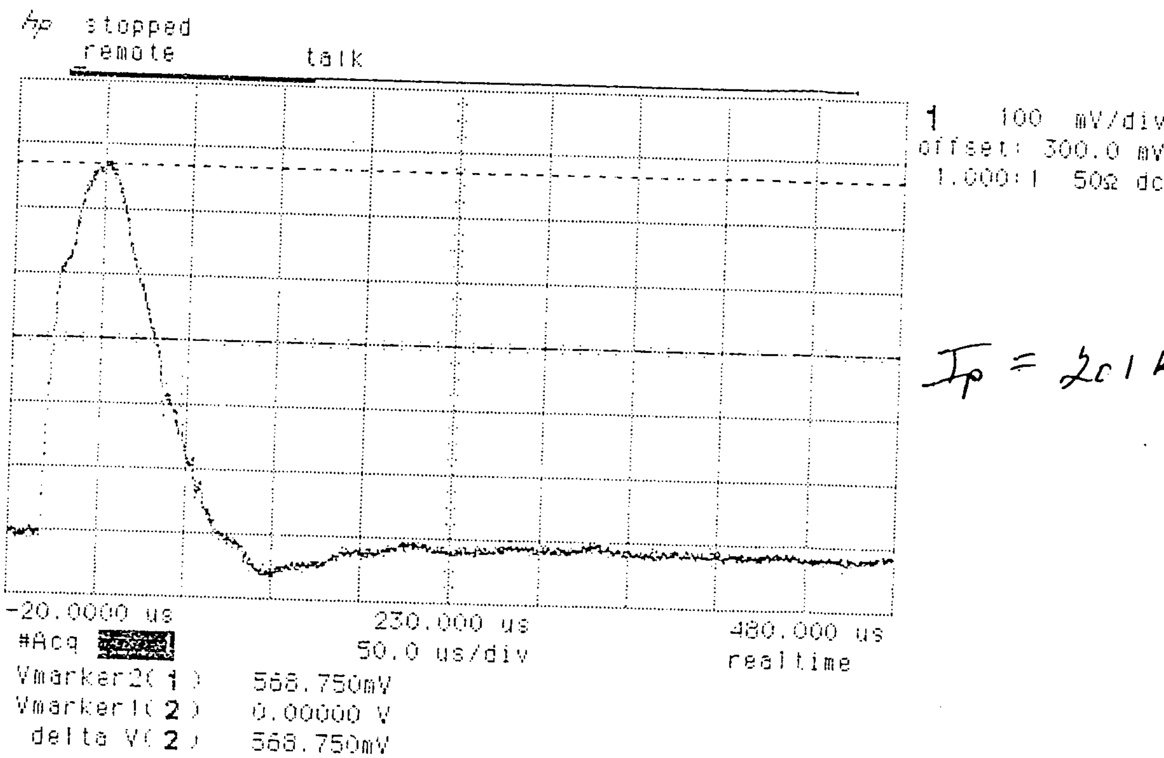
APPENDIX C

TEST DATA

Filename: SRBCALA1.RAW
Date: 01-17-1995
Time: 10:02:14

Action Integral(Channel 1) = 1.455056E-05 $(708)^2(500)^2 = 1.82 E6 \; A^2 sec$

Quick-Look Plot from HP54510A
GPIBaddrss 07 Channel 1



$I_p = 201$ kA

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

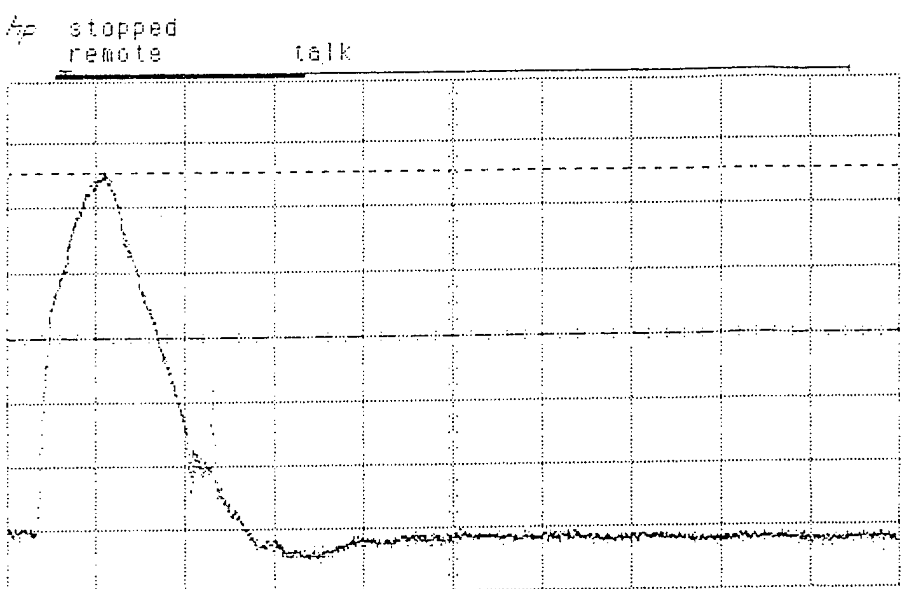
Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

Figure C-1. Measurement of Component A Calibration Waveform on the Frustum Panel.

Filename: SRBCALA2.RAW
Date: 01-17-1995
Time: 10:16:32

Action Integral(Channel 1) = 1.438409E-05 $(708)^2(500)^2 = 1.80E6\ A^2 \cdot sec.$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 196\ KA$

-20.0000 us 230.000 us 480.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 553.125mV
Vmarker1(2) 0.00000 V
delta V(2) 553.125mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

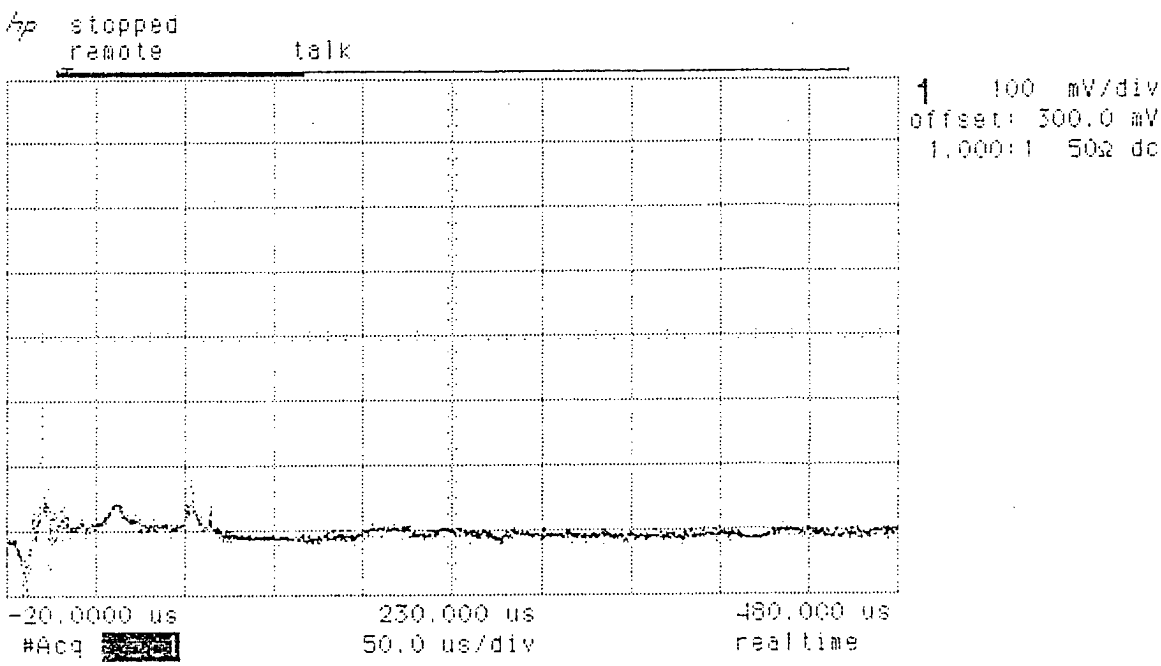
Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

Figure C-2. Measurement of Component A Calibration Waveform on the Aft Skirt Panel.

Filename: SS106#9A.RAW Bad Data
Date: 01-17-1995
Time: 12:27:17

Action Integral(Channel 1) = 1.555956E-07

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1



1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

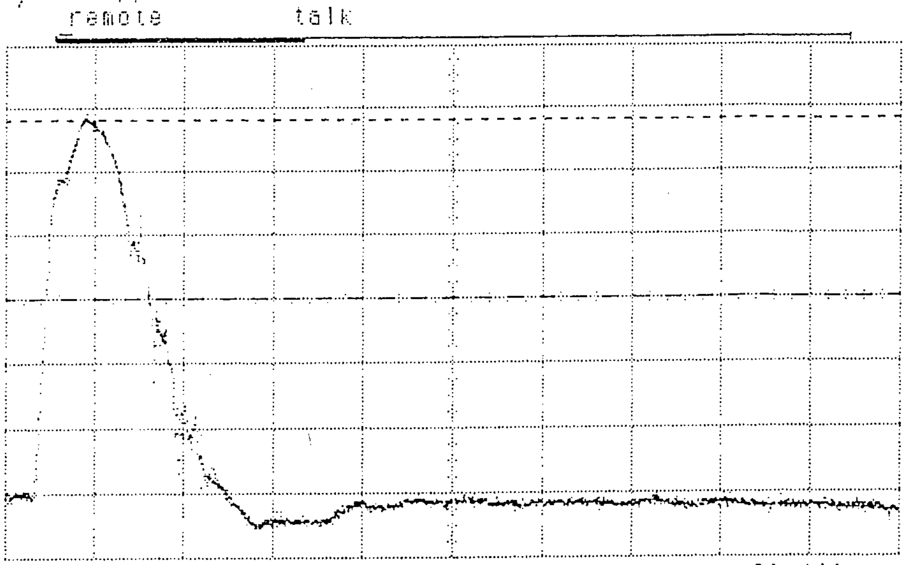
Figure C-3. Measurement of Component A Waveform on Panel Q6#9 (Instrumentation Malfunction).

Filename: SS2Q6#9A.RAW
Date: 01-17-1995
Time: 13:18:04

Action Integral(Channel 1) = 1.552087E-05 $(708)^2 (500\ A/V)^2 = 1.94\ E6\ A^2 \cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 206\ kA$

-20.0000 us 230.000 us 480.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 581.250mV
Vmarker1(2) 0.00000 V
delta V(2) 581.250mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

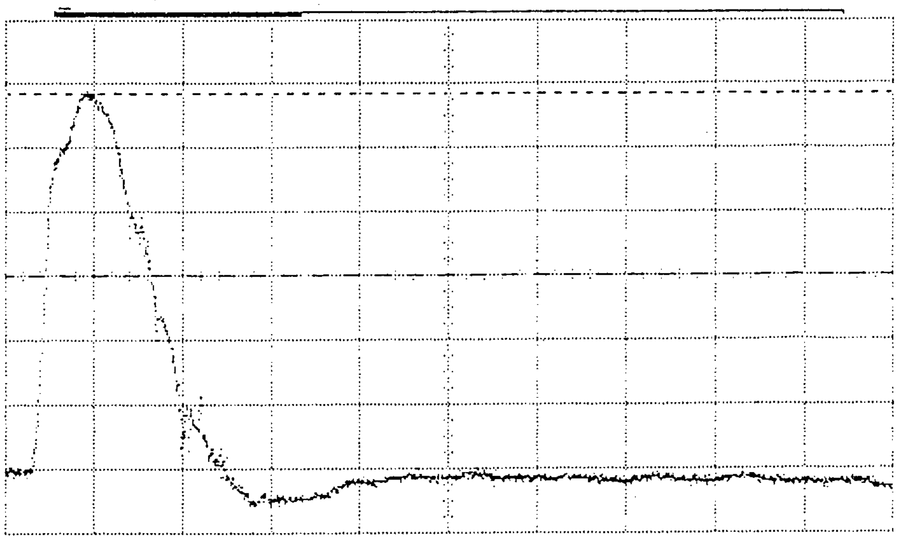
Figure C-4. Measurement of Component A Waveform on Panel Q6#9.

Filename: S1Q6#10A.RAW
Date: 01-17-1995
Time: 14:36:07

Action Integral(Channel 1) = 1.56301E-05 $(708)^2(500)^2 = 1.95E6\ A^2\cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 207\ kA$

-20.0000 us 230.000 us 460.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 584.375mV
Vmarker1(2) 0.00000 V
delta V(2) 584.375mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

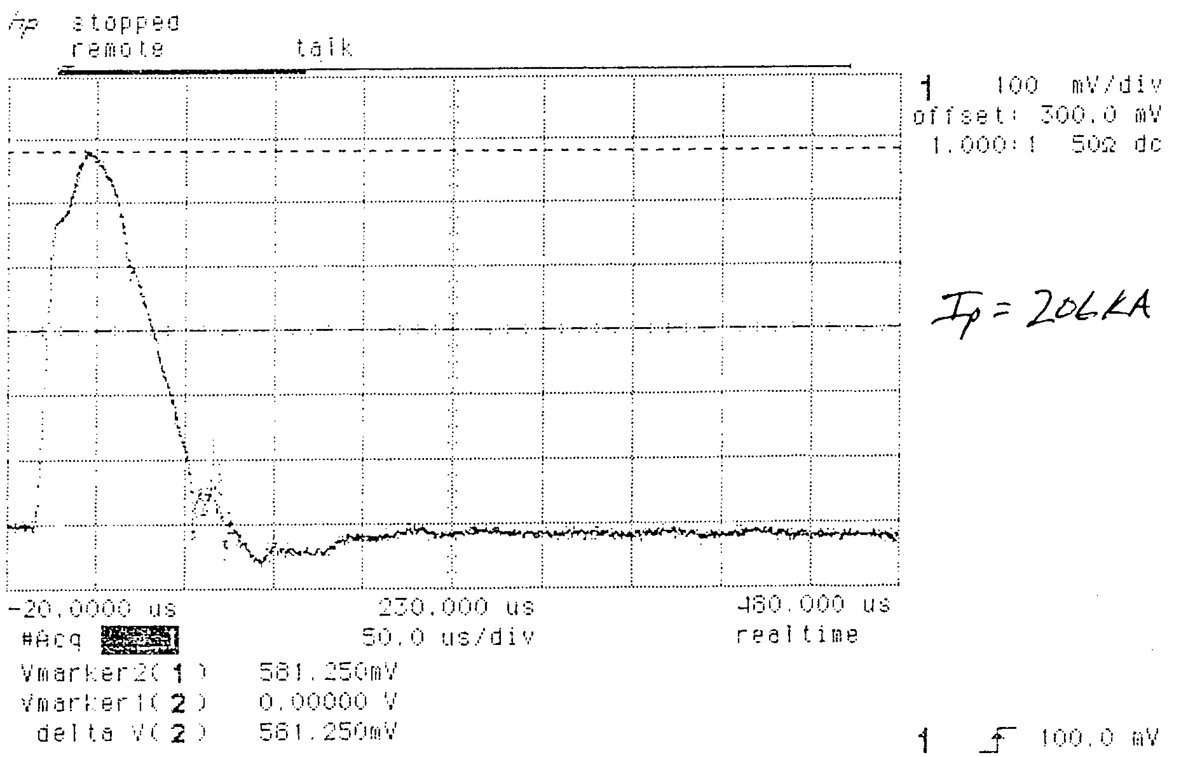
Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

Figure C-5. Measurement of Component A Waveform on Panel Q6#10.

Filename: S1Q13#2A.RAW
Date: 01-17-1995
Time: 14:42:57

Action Integral(Channel 1) = 1.526847E-05 $(708)^2(500)^2 = 1.92\,E6\ A^2\cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1



	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

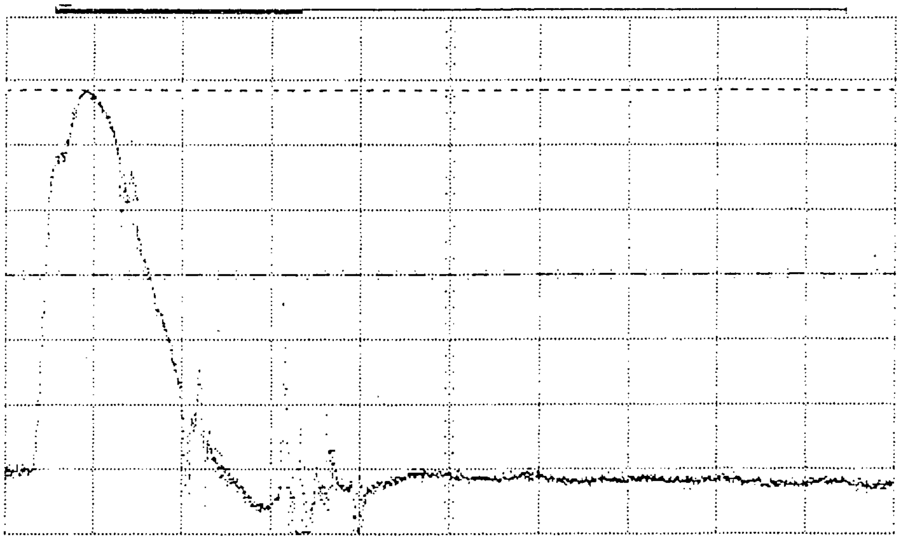
Figure C-6. Measurement of Component A Waveform on Panel Q13#2.

Filename: S1Q11#6A.RAW
Date: 01-17-1995
Time: 15:00:34

Action Integral(Channel 1) = 1.578818E-05 $(708)^2 (500)^2 = 1.97E6\ A^2\cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 207\ kA$

-20.0000 us 230.000 us 480.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 584.375mV
Vmarker1(2) 0.00000 V
delta V(2) 584.375mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

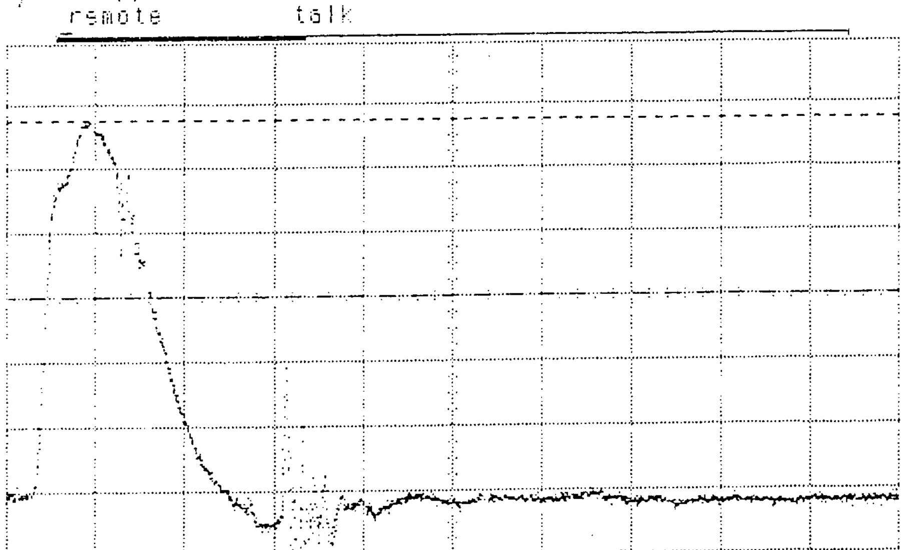
Figure C-7. Measurement of Component A Waveform on Panel Q11#6.

Filename: S1Q11#8A.RAW
Date: 01-17-1995
Time: 15:09:42

Action Integral(Channel 1) = 1.501047E-05 $(708)^2 (500A/v)^2 = 1.88\ E6\ A^2 \cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 204\ kA$

-20.0000 us 230.000 us 480.000 us
#Acq [illegible] 50.0 us/div realtime

Vmarker2(1) 575.000mV
Vmarker1(2) 0.00000 V
delta V(2) 575.000mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

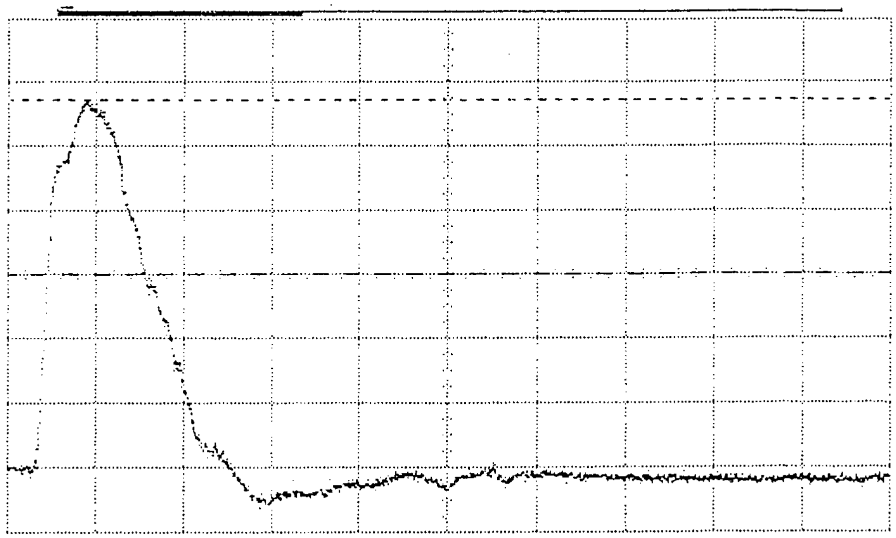
Figure C-8. Measurement of Component A Waveform on Panel Q11#8.

Filename: S1Q11#9A.RAW
Date: 01-17-1995
Time: 15:23:49

Action Integral(Channel 1) = 1.472124E-05 $(708)^2(500A/v)^2 = 1.84E6\ A^2\cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 202\ kA$

-20.0000 us 230.000 us 480.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 571.875mV
Vmarker1(2) 0.00000 V
delta V(2) 571.875mV

1 ⎍ 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

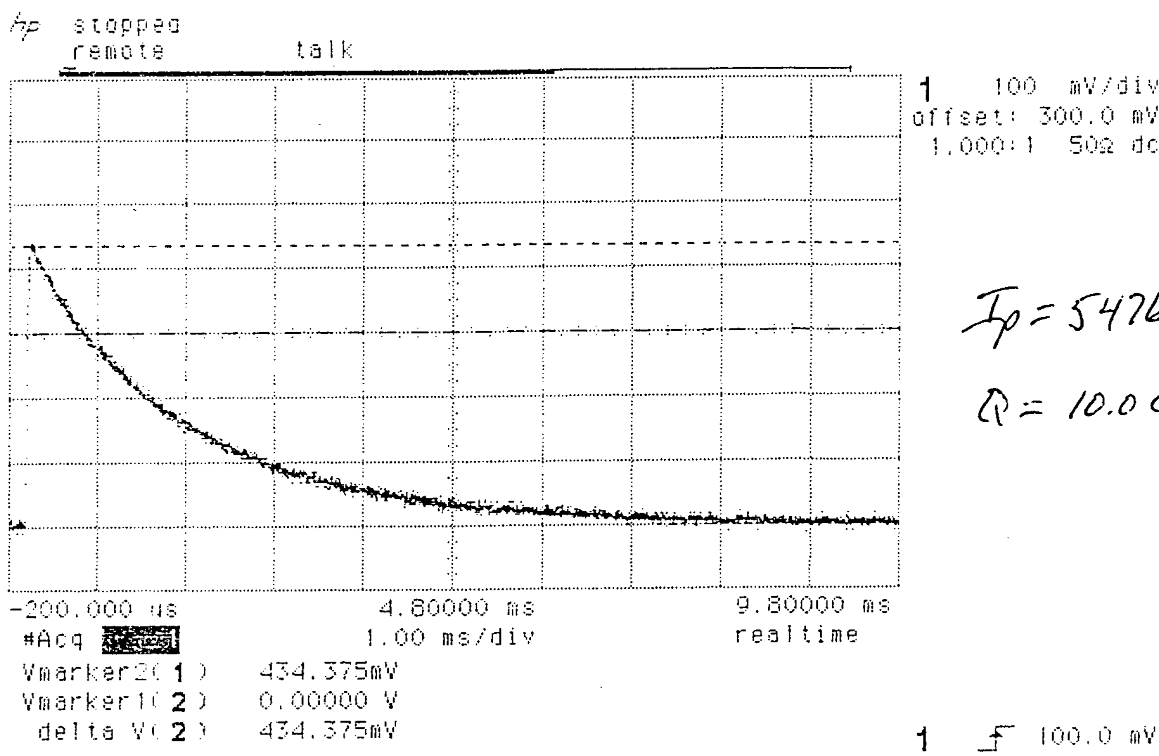
Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

Figure C-9. Measurement of Component A Waveform on Panel Q11#9.

Filename: SRBCALB1.RAW
Date: 01-18-1995
Time: 08:24:51

Action Integral(Channel 1) = ~~[illegible]~~

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1



$I_p = 5476$ A

$Q = 10.0$ C

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

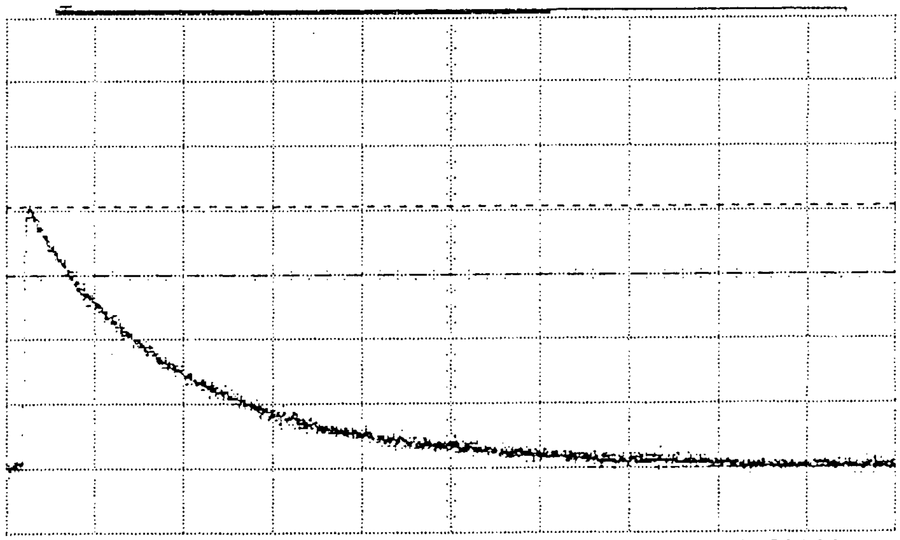
Figure C-10. Measurement of Component B Calibration Waveform on the Frustum Panel.

Filename: SRBCALB2.RAW
Date: 01-18-1995
Time: 08:54:49

Action Integral(Channel 1) = [illegible]

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 5123A$

$Q = 9.3C$

-200.000 us 4.80000 ms 9.80000 ms
#Acq [illegible] 1.00 ms/div realtime

Vmarker2(1) 406.250mV
Vmarker1(2) 0.00000 V
delta V(2) 406.250mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

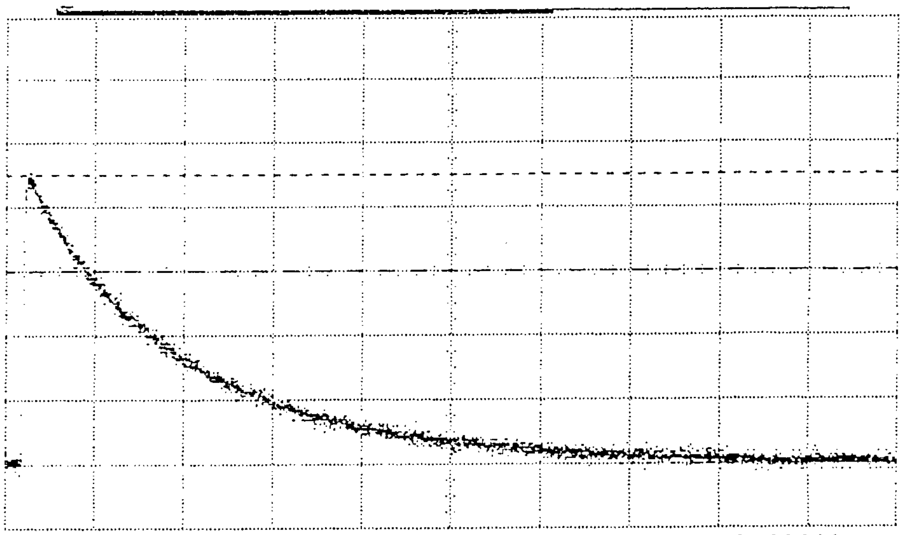
Figure C-11. Measurement of Component B Calibration Waveform on the Aft Skirt Panel.

Filename: SS1Q6#9B.RAW
Date: 01-18-1995
Time: 09:05:24

Action Integral(Channel 1) = 1

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 5679$ A
$Q = 10.3$ C

-200.000 us 4.80000 ms 9.80000 ms
#Acq 1.00 ms/div realtime
Vmarker2(1) 450.000mV
Vmarker1(2) 0.00000 V
delta V(2) 450.000mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

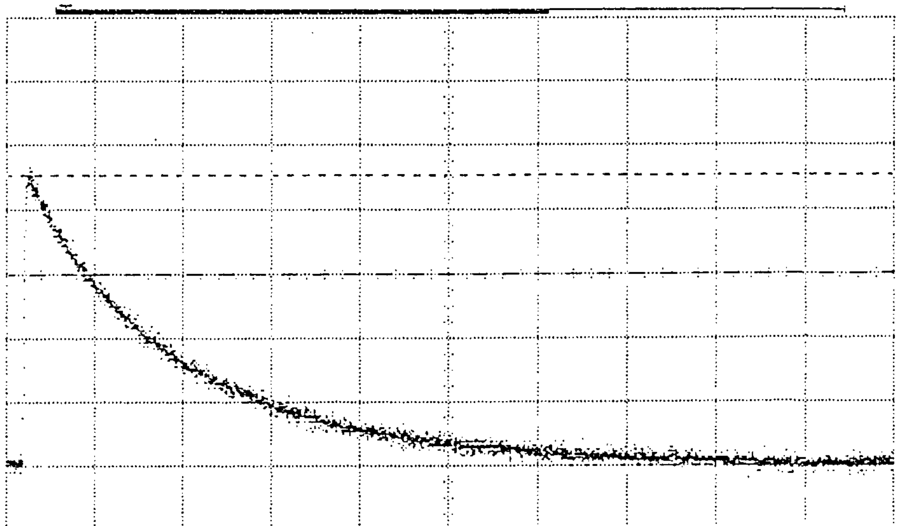
Figure C-12. Measurement of Component B Waveform on Panel Q6#9.

Filename: S1Q6#10B.RAW
Date: 01-18-1995
Time: 09:16:50

Action Integral(Channel 1) = ~~[illegible]~~

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 5716A$

$Q = 10.3 C$

-200.000 us 4.80000 ms 9.80000 ms
#Acq [illegible] 1.00 ms/div realtime

Vmarker2(1) 453.125mV
Vmarker1(2) 0.00000 V
delta V(2) 453.125mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

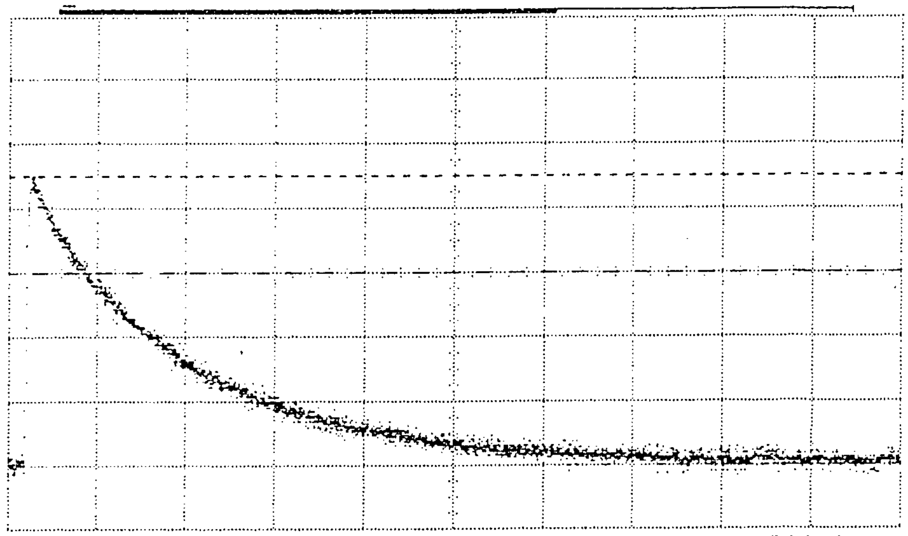
Figure C-13. Measurement of Component B Waveform on Panel Q6#10.

Filename: S1Q13#2B.RAW
Date: 01-18-1995
Time: 09:27:43

Action Integral(Channel 1) = ~~[illegible]~~

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 5679\,A$

$Q = 10.3\,C$

-200.000 us 4.80000 ms 9.80000 ms
#Acq 1.00 ms/div realtime
Vmarker2(1) 450.000mV
Vmarker1(2) 0.00000 V
delta V(2) 450.000mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

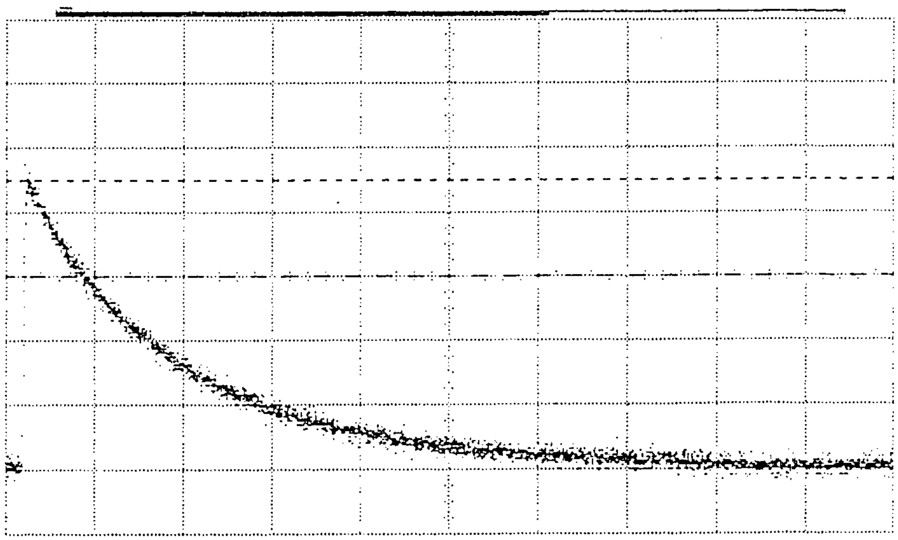
Figure C-14. Measurement of Component B Waveform on Panel Q13#2.

Filename: S1Q11#6B.RAW
Date: 01-18-1995
Time: 09:37:29

Action Integral(Channel 1) = ~~[illegible]E-04~~

Quick-Look Plot from HP54510A
GPIBaddress 07   Channel 1

hp stopped
remote   talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 56.79A$
$Q = 10.3$ C.

-200.000 us   4.80000 ms   9.80000 ms
#Acq [illegible]   1.00 ms/div   realtime

Vmarker2(1) 450.000mV
Vmarker1(2) 0.00000 V
delta V(2) 450.000mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

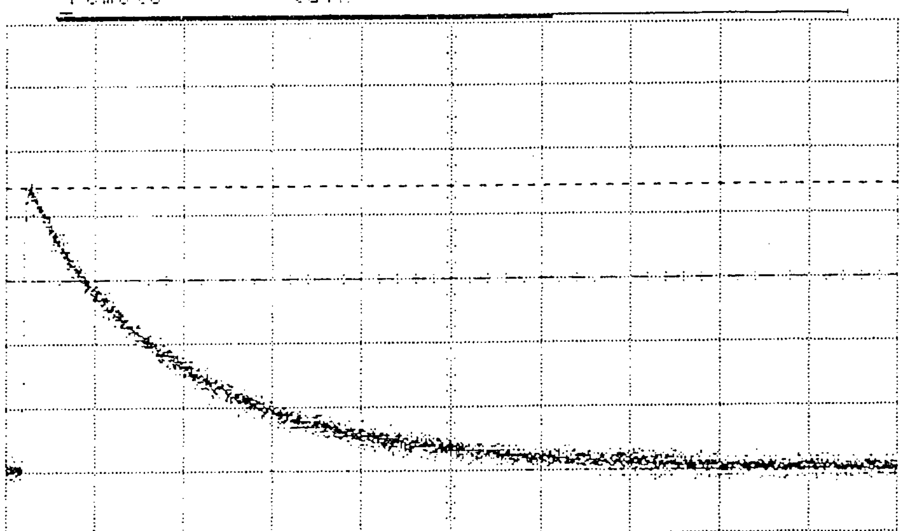
Figure C-15. Measurement of Component B Waveform on Panel Q11#6.

Filename: S1Q11#8B.RAW
Date: 01-18-1995
Time: 09:46:07

Action Integral(Channel 1) = ~~[illegible]~~

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

I_p = 5603A
Q = 10.1C

-200.000 us 4.80000 ms 9.80000 ms
#Acq 1.00 ms/div realtime
Vmarker2(1) 443.750mV
Vmarker1(2) 0.00000 V
delta V(2) 443.750mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

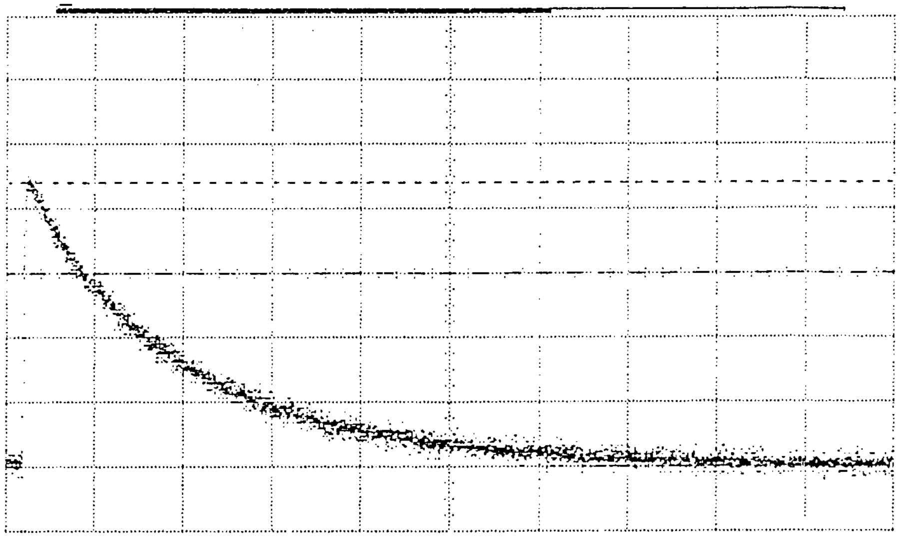
Figure C-16. Measurement of Component B Waveform on Panel Q11#8.

Filename: S1Q11#9B.RAW
Date: 01-18-1995
Time: 09:54:00

Action Integral(Channel 1) = ~~[illegible]~~

Quick-Look Plot from HP54510A
GPIBaddress 07   Channel 1

stopped
remote   talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 5565A$

$Q = 10.1C$

-200.000 us   4.80000 ms   9.80000 ms
#Acq [illegible]   1.00 ms/div   realtime
Vmarker2(1) 440.625mV
Vmarker1(2) 0.00000 V
delta V(2) 440.625mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel 1
Trigger Level(s)
Channel 1 = 100,000 mV (noise reject OFF)
HoldOff = 40.000 n/s

Figure C-17. Measurement of Component B Waveform on Panel Q11#9.

Filename: SRBCALC1.RAW
Date: 01-18-1995
Time: 13:41:13

Action Integral(Channel 1) = ~~[illegible]~~

Charge Integral(Channel 1) = .7603593 (20) (13.16 A/V) = 200.1 C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [1] ____________________Status: Acquisition Complete____
LLO MTA

Range [3.0 V]
Offset [1.000 V]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [1:1]

Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

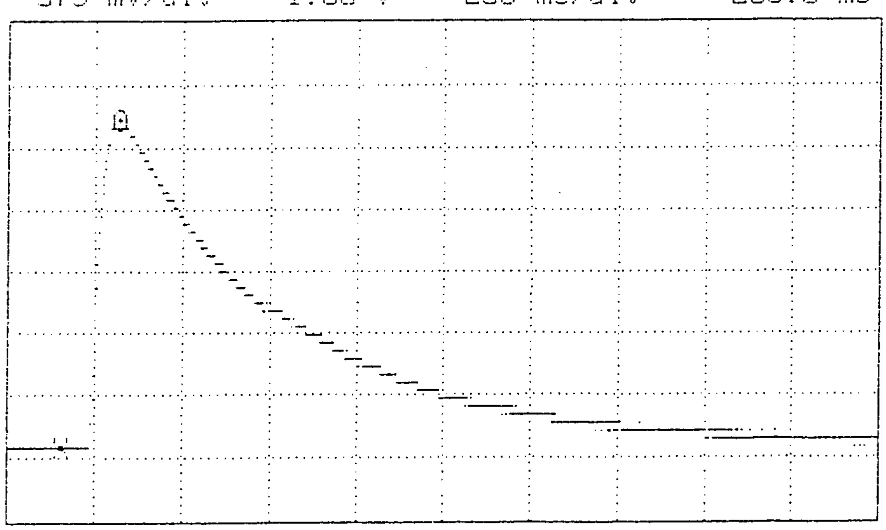
1:

Cursor 0

V_x -64.5 mV
T_x -76.00 ms

V_0 1.92 V
T_0 52.00 ms

ΔV 1.98 V
ΔT 128.0 ms



I_p = 521 A

Figure C-18. Measurement of Component C Calibration waveform on the Frustum Panel.

Filename: SS1Q6#9C.RAW
Date: 01-18-1995
Time: 14:11:01

Action Integral(Channel 1) = ~~[illegible]~~

Charge Integral(Channel 1) = .7608432 (20)(13.16 A/V) = 200.2 C

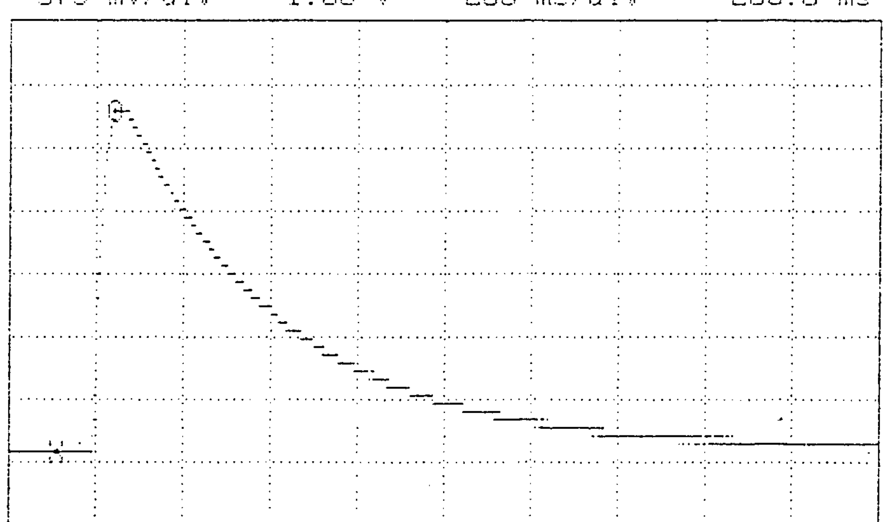
Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [1] ____________________Status: Acquisition Complete____
LLO MTA

Range [3.0 V]
Offset [1.000 V]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [[illegible]]

Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms



Cursor X

V_x -64.5 mV
T_x -90.00 ms

V_o 1.97 V
T_o 42.00 ms

ΔV 2.03 V
ΔT 132.0 ms

$I_p = 534A$

$Q = 200.2 C$

Figure C-19. Measurement of Component C Waveform on Panel Q6#9.

Filename: SS2Q6#9C.RAW
Date: 01-18-1995
Time: 15:08:37

Action Integral(Channel 1) = .~~[illegible]~~

Charge Integral(Channel 1) = .7709062 (20)(13.16 A/V) = 203 C

Quick-Look Plot from HP54200A
GPIBaddress 11   Channel 1

Channel [1] __________________Status: Acquisition Complete____
LLO MTA

Range [3.00 V]
Offset [1.000 V]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [1:1]

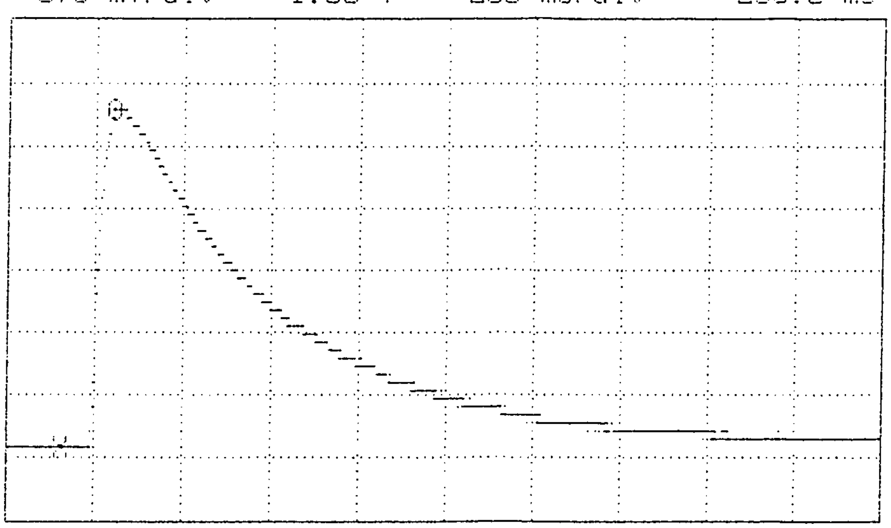
Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

Cursor 0

V_x -64.5 mV
T_x -76.00 ms

V_0 1.97 V
T_0 42.00 ms

ΔV 2.03 V
ΔT 118.0 ms



$I_p = 534\ A$

Figure C-20. Measurement of Component C Waveform on Panel Q6#9.

Filename: S1Q6#10C.RAW
Date: 01-18-1995
Time: 15:24:49

Action Integral(Channel 1) = ~~[illegible]~~

Charge Integral(Channel 1) = .7744863 (20)(13.16 A/V) = 204 C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [1] __________________Status: Acquisition Complete____
LLO MTA SHIFT

Range [3.0 V]
Offset [1.000 V]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [1:1]

Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

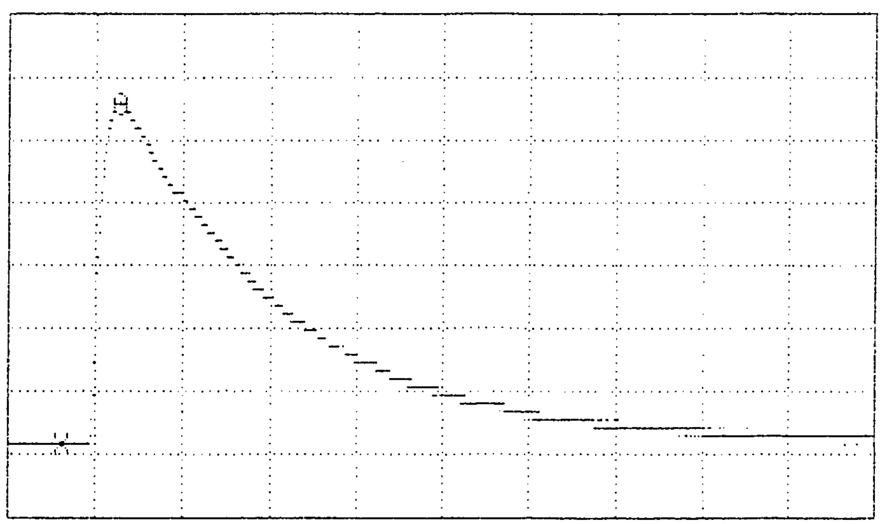
1:

Cursor 0

V_x -64.5 mV
T_x -76.00 ms

V_0 1.97 V
T_0 54.00 ms

ΔV 2.03 V
ΔT 130.0 ms



$I_p = 534A$

Figure C-21. Measurement of Component C Waveform on panel Q6#10.

Filename: S1Q13#2C.RAW
Date: 01-18-1995
Time: 15:45:55

Action Integral(Channel 1) = ~~.8724405~~

Charge Integral(Channel 1) = .774196 (20)(13.16 A/V) = 204 C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

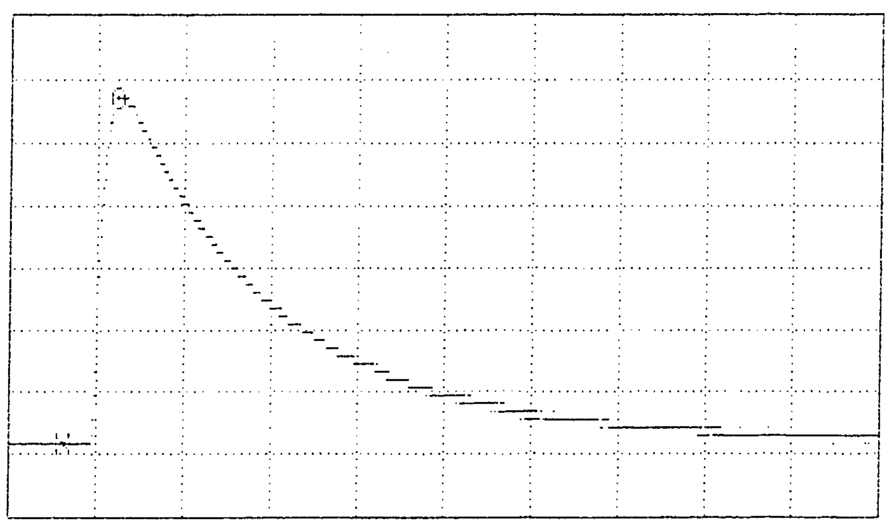
Channel [1] ____________________Status: Acquisition Complete____
LLO MTA

Range 3.0 V
Offset 1.000 V

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [1:1]

Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

1:



Cursor 0

V_x -64.5 mV
T_x -76.00 ms

V_0 2.02 V
T_0 44.00 ms

ΔV 2.08 V
ΔT 120.0 ms

$I_p = 547A$

Figure C-22. Measurement of Component C Waveform on Panel Q13#2.

Filename: S1Q11#6C.RAW
Date: 01-18-1995
Time: 15:51:24

Action Integral(Channel 1) = ~~[illegible]~~

Charge Integral(Channel 1) = .7848396 (20)(13.16 A/V) = 207C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [1] ____________________Status: Acquisition Complete____
LLO MTA

Range [3.0 V]
Offset [1.000 V]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [illegible]

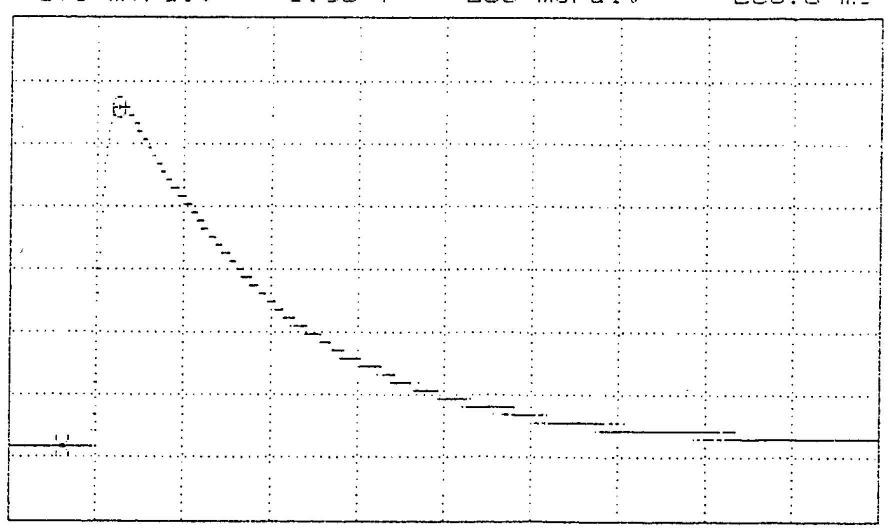
Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

Cursor 0

V_x -64.5 mV
T_x -76.00 ms

V_0 1.97 V
T_0 50.00 ms

ΔV 2.03 V
ΔT 126.0 ms



$I_p = 534A$

Figure C-23. Measurement of Component C Waveform on Panel Q11#6.

Filename: SIQ11#8C.RAW
Date: 01-18-1995
Time: 16:05:15

Action Integral(Channel 1) = .~~[illegible]~~

Charge Integral(Channel 1) = .7560051 (20) (13.16 A/V) = 199C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [illegible] __________________Status: Acquisition Complete____
LLO MTA

Range [illegible]
Offset [illegible]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [illegible]

Graph [illegible] 375 mV/div 1.00 V 200 ms/div -200.0 ms

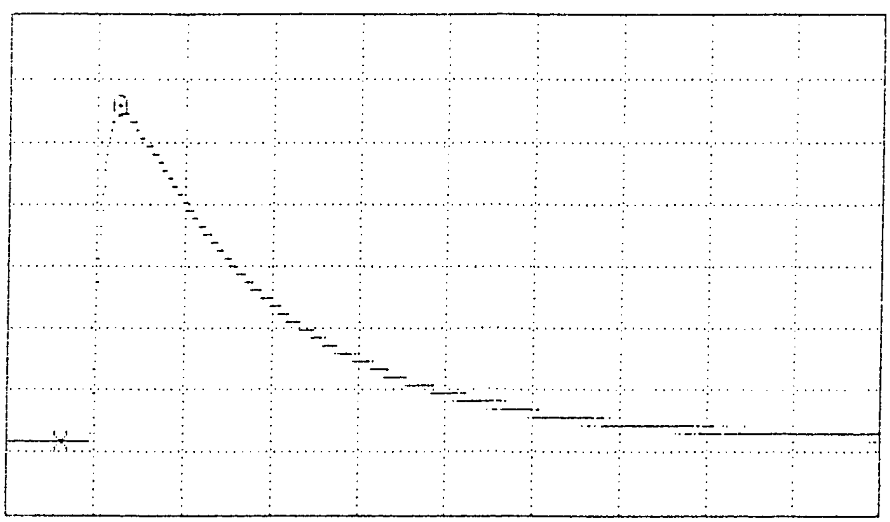
1:

Cursor 0

V_X -64.5 mV
T_X -76.00 ms

V_0 1.97 V
T_0 48.00 ms

ΔV 2.03 V
ΔT 124.0 ms



$I_p = 534A$

Figure C-24. Measurement of Component C Waveform on Panel Q11#8.

Filename: S2Q11#9C.RAW
Date: 01-18-1995
Time: 16:20:15

Action Integral(Channel 1) = ~~.3245514~~

Charge Integral(Channel 1) = .7694548 (2.0)(13.16 A/V) = 203 C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [1] __________________Status: Acquisition Complete____
LLO MTA

Range [3.0 V]
Offset [1.000 V]

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [1 MΩ]

Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

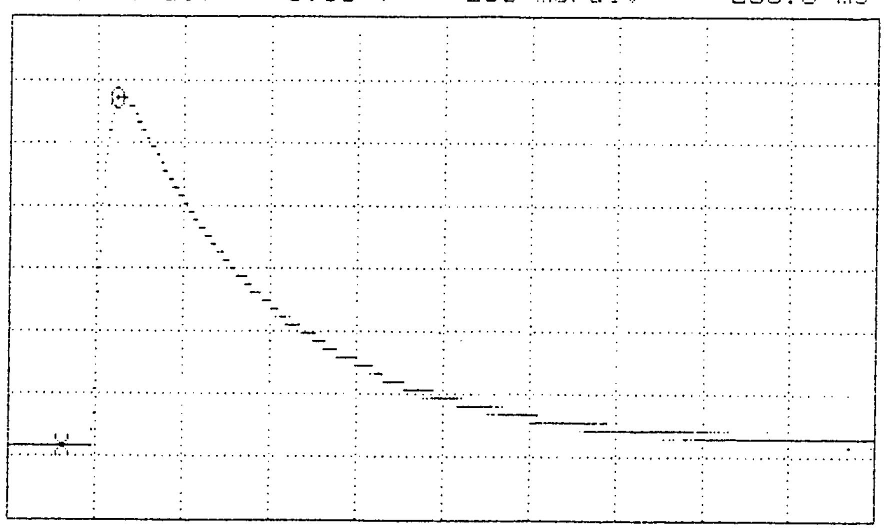
1:

Cursor 0

V_x -64.5 mV
T_x -76.00 ms

V_0 2.02 V
T_0 44.00 ms

ΔV 2.08 V
ΔT 120.0 ms



$I_p = 547 A$

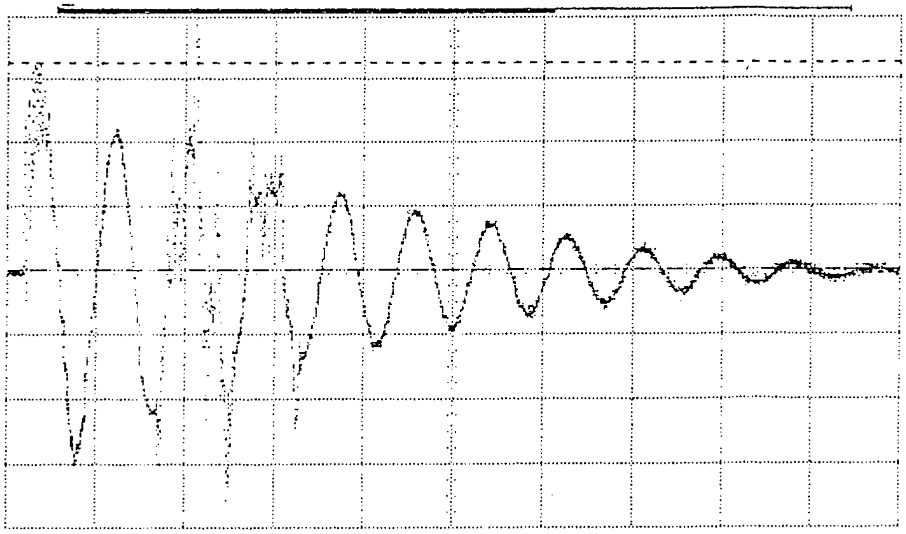
Figure C-25. Measurement of Component C Waveform on Panel Q11#9.

Filename: SRBCALD1.RAW
Date: 01-20-1995
Time: 13:14:54

Action Integral(Channel 1) = 4.916749E-06 $(400\,A/V)^2(708)^2 = 0.39\times10^6\,A^2 s$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 92\,kA$

-10.0000 us 240.000 us 490.000 us
#Acq 50.0 us/div realtime
Vmarker2(1) 325.000mV
Vmarker1(2) 0.00000 V
delta V(2) 325.000mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

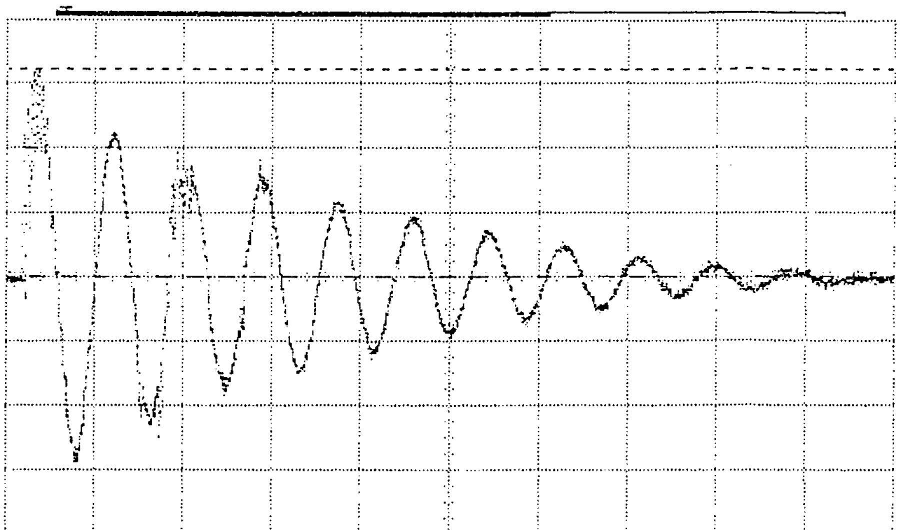
Figure C-26. Measurement of Component D Calibration Waveform on the Frustum Panel.

Filename: SRBCALD2.RAW
Date: 01-20-1995
Time: 13:32:44

Action Integral(Channel 1) = 4.379138E-06 $(400\,A/v)^2(708)^2 = 0.35 \times 10^6\,A^2 \cdot s$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 91\,kA$

-10.0000 us 240.000 us 490.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 321.875mV
Vmarker1(2) 0.00000 V
delta V(2) 321.875mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

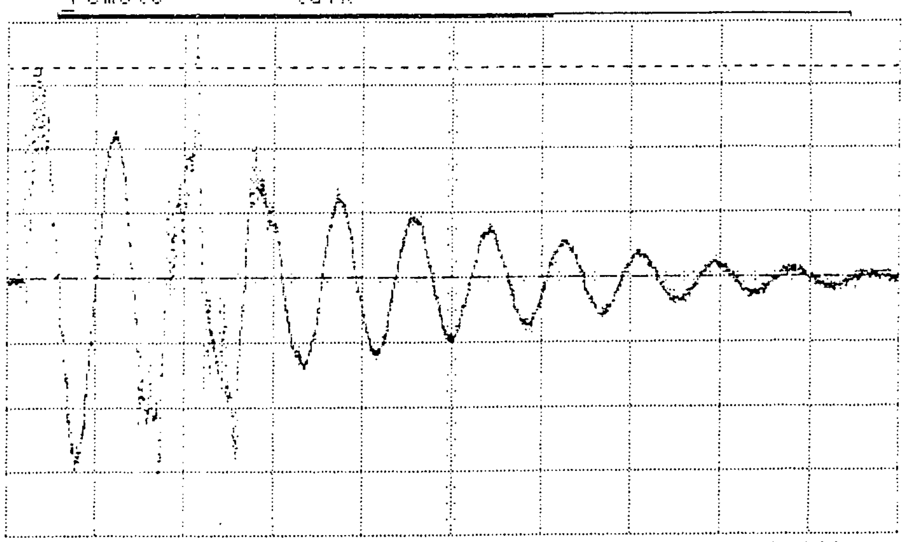
Figure C-27. Measurement of Component D Calibration Waveform on the Aft Skirt Panel.

Filename: SS1Q6#9D.RAW
Date: 01-20-1995
Time: 13:40:27

Action Integral(Channel 1) = 4.868863E-06 $(400\,A/V)^2 (708)^2 = 0.39 \times 10^6 A^2$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 93\,kA$

-10.0000 us 240.000 us 490.000 us
#Acq 50.0 us/div realtime

Vmarker2(1) 328.125mV
Vmarker1(2) 0.00000 V
delta V(2) 328.125mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

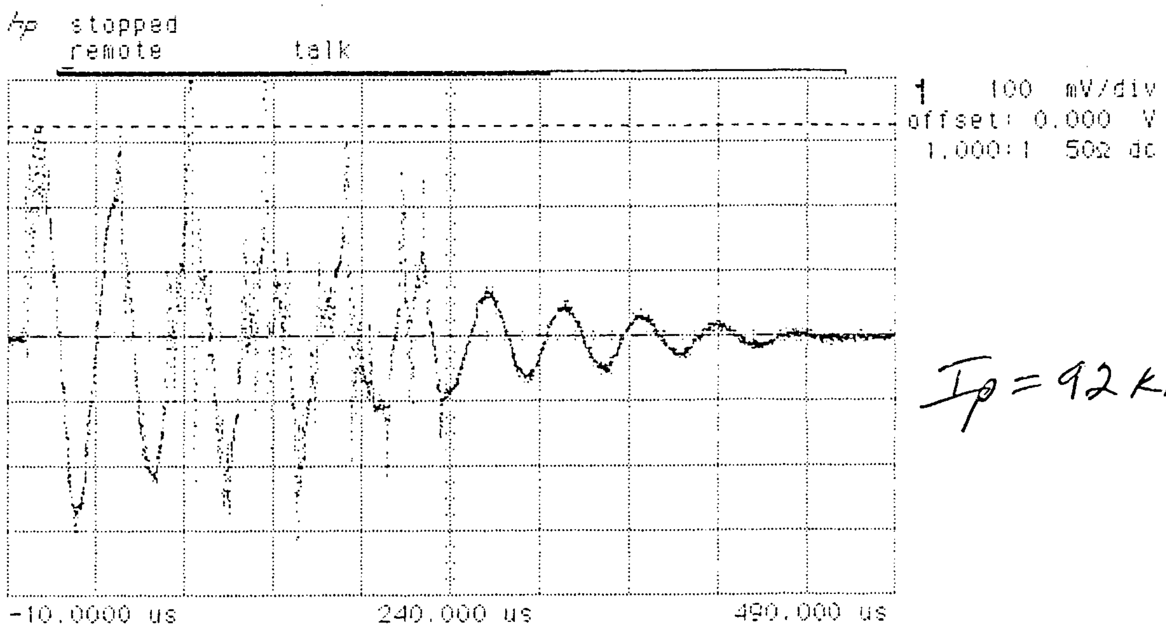
Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

Figure C-28. Measurement of Component D Waveform on Panel Q6#9.

Filename: S1Q6#10D.RAW
Date: 01-20-1995
Time: 13:51:08

Action Integral(Channel 1) = 5.324274E-06 $(400\,A/V)^2/(708)^2 = 0{,}42 \times 10^6\,A^2 \cdot s$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1



$I_p = 92\,kA$

#Acq [redacted]
Vmarker2(1) 325.000mV
Vmarker1(2) 0.00000 V
delta V(2) 325.000mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

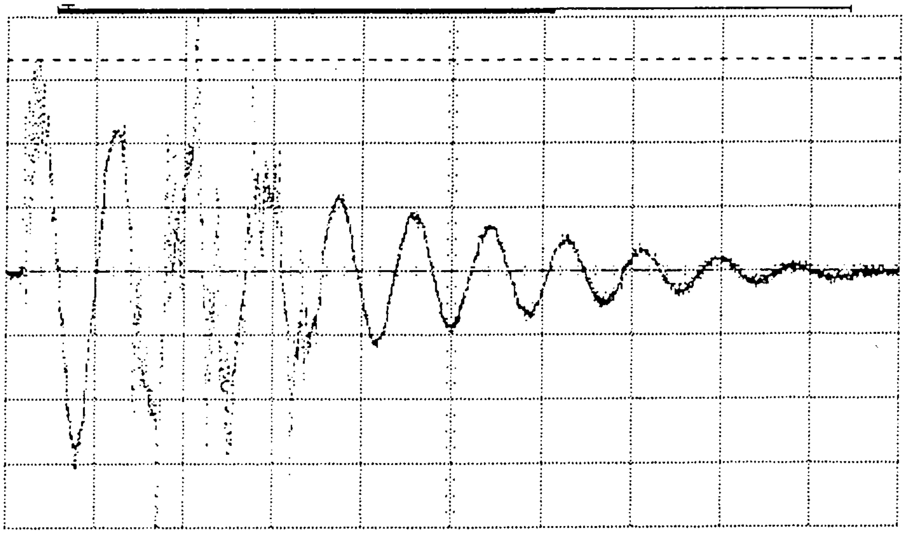
Figure C-29. Measurement of Component D Waveform on Panel Q6#10.

Filename: S1Q13#2D.RAW
Date: 01-20-1995
Time: 14:02:05

Action Integral(Channel 1) = 5.029919E-06 $(400\ A/V)^2 (708)^2 = 0.40 \times 10^6\ A^2 s$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 94\ kA$

-10.0000 us 240.000 us 490.000 us
#Acq 1 50.0 us/div realtime

Vmarker2(1) 331.250mV
Vmarker1(2) 0.00000 V
delta V(2) 331.250mV

1 ↑ 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

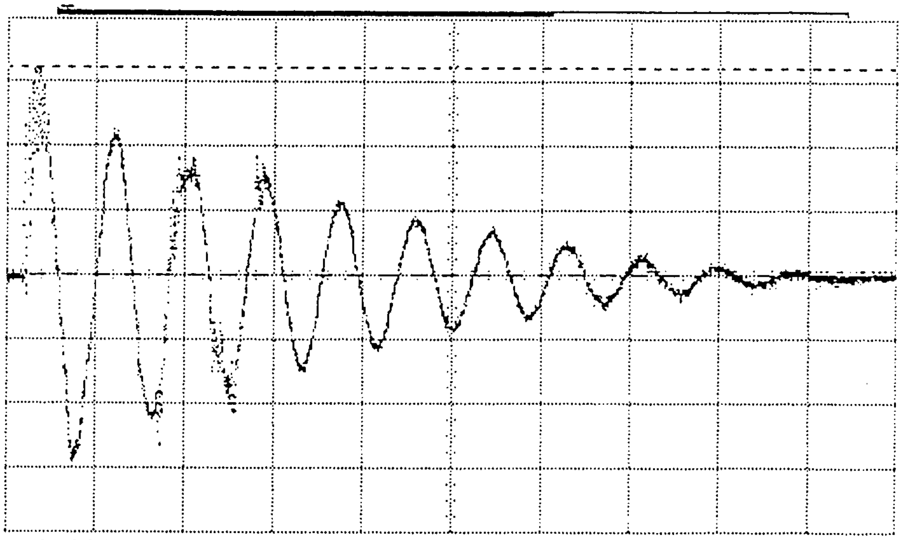
Figure C-30. Measurement of Component D Waveform on Panel Q13#2.

Filename: S1Q11#6D.RAW
Date: 01-20-1995
Time: 14:12:13

Action Integral(Channel 1) = 4.319782E-06 $(400 A/v)^2 (708)^2 = 0.35 \times 10^6 A^2 \cdot sc$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 91KA$

-10.0000 us 240.000 us 490.000 us
#Acq 1 50.0 us/div realtime
Vmarker2(1) 321.875mV
Vmarker1(2) 0.00000 V
delta V(2) 321.875mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

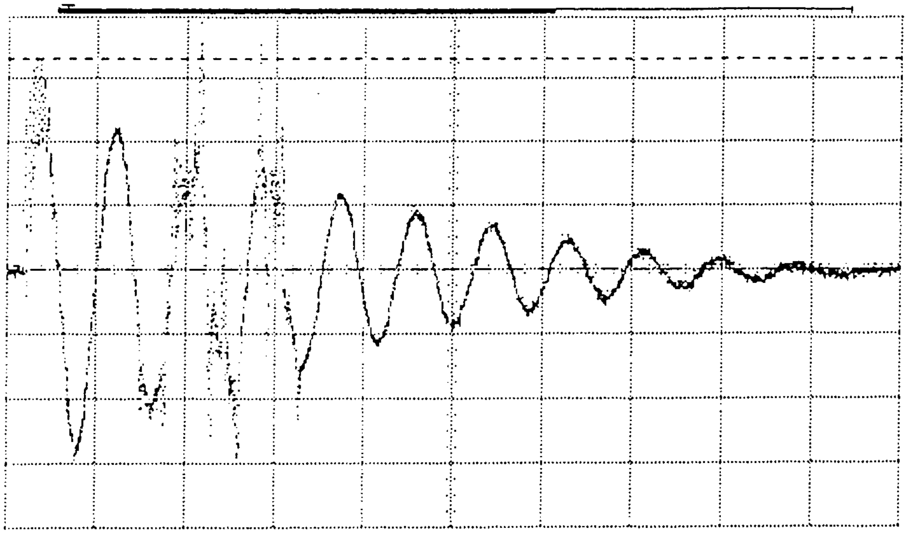
Figure C-31. Measurement of Component D Waveform on Panel Q11#6.

Filename: S1Q11#8D.RAW
Date: 01-20-1995
Time: 14:21:55

Action Integral(Channel 1) = 4.840104E-06 $(400\,A/V)^2(908)^2 = 0.39\times10^6\,A^2\cdot sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 94\,kA$

-10.0000 us 240.000 us 490.000 us
#Acq 50.0 us/div realtime
Vmarker2(1) 331.250mV
Vmarker1(2) 0.00000 V
delta V(2) 331.250mV

1 ⨍ 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

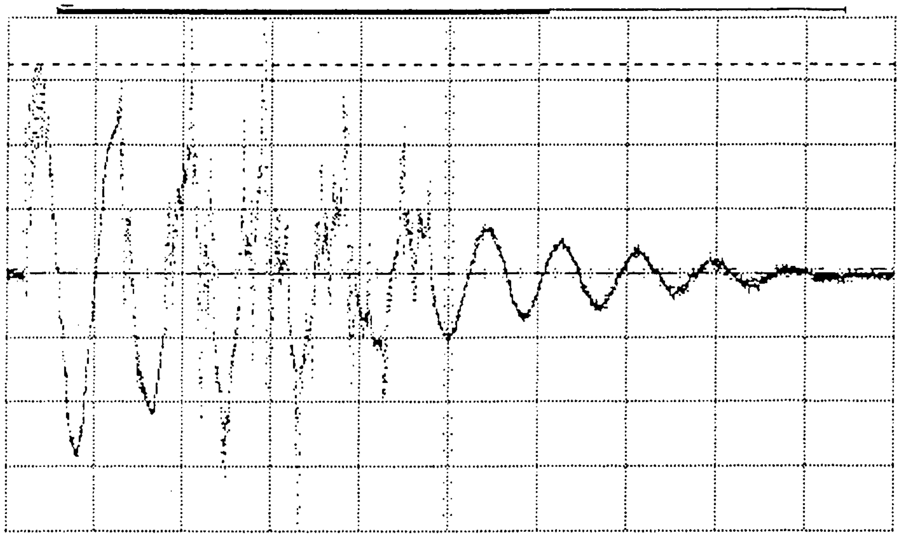
Figure C-32. Measurement of Component D Waveform on Panel Q11#8.

Filename: S1Q11#9D.RAW
Date: 01-20-1995
Time: 14:32:36

Action Integral(Channel 1) = 5.390028E-06 $(400A/V)^2(708)^2 = 0{,}43\times10^{6}A^2\cdot s$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 0.000 V
1.000:1 50Ω dc

$I_p = 92\,KA$

-10.0000 us 240.000 us 490.000 us
#Acq [illegible] 50.0 us/div realtime
Vmarker2(1) 325.000mV
Vmarker1(2) 0.00000 V
delta V(2) 325.000mV

1 ⨍ 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	0.00000 V	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

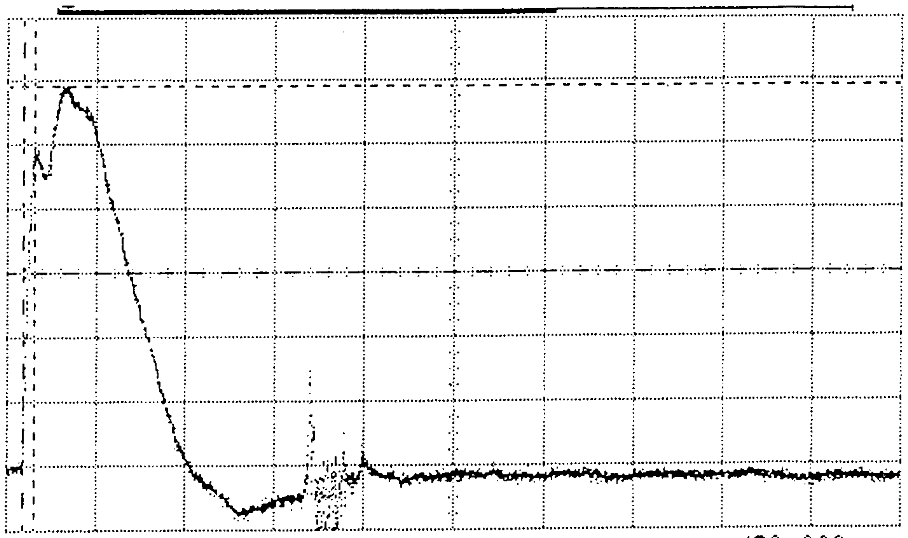
Figure C-33. Measurement of Component D Waveform on Panel Q11#9.

Filename: TTC5#16A.RAW
Date: 01-20-1995
Time: 14:50:30

Action Integral(Channel 1) = 1.49809E-05 $(500\ A/v)^2 (708)^2 = 1.88 \times 10^6\ A^2 \cdot sec.$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 209\ kA$

-10.0000 us 240.000 us 490.000 us
#Acq 1 50.0 us/div realtime

Vmarker2(1)	590.625mV	stop marker:	5.60000us
Vmarker1(2)	0.00000 V	start marker:	-1.20000us
delta V(2)	590.625mV	delta t:	6.80000us
		1/delta t:	147.059kHz

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

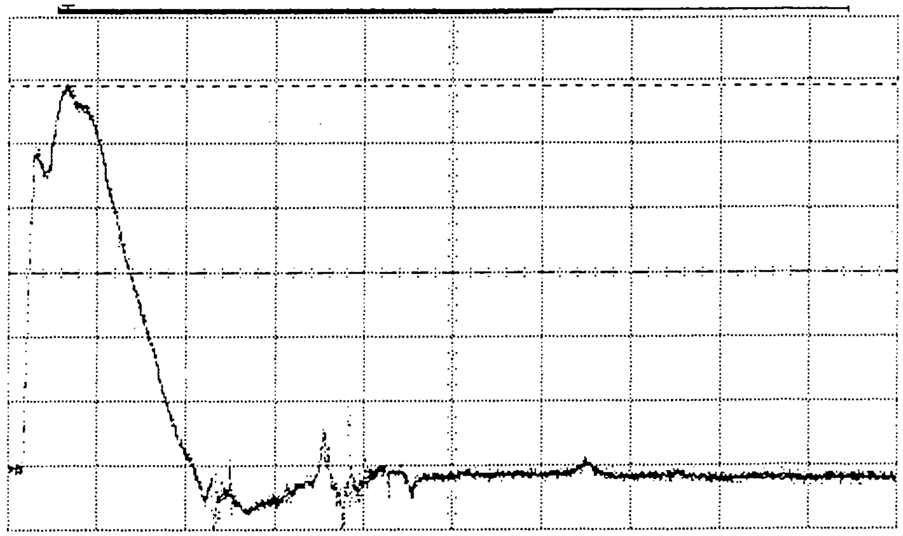
Figure C-34. Measurement of Component A Waveform on Panel TTC5#16.

Filename: TC5#13AC.RAW
Date: 01-20-1995
Time: 15:20:46

Action Integral(Channel 1) = 1.497187E-05 $(500 A/V)^2 (708)^2 = 1.88 \times 10^6 A^2 sec$

Quick-Look Plot from HP54510A
GPIBaddress 07 Channel 1

hp stopped
remote talk



1 100 mV/div
offset: 300.0 mV
1.000:1 50Ω dc

$I_p = 209\ kA$

-10.0000 us 240.000 us 490.000 us
#Acq 1 50.0 us/div realtime
Vmarker2(1) 590.625mV
Vmarker1(2) 0.00000 V
delta V(2) 590.625mV

1 100.0 mV

	Sensitivity	Offset	Probe	Coupling	Impedance
Channel 1	100 mV/div	300.000 mV	1:1	dc	50 ohm

Trigger Mode: Edge
On the Positive Edge of Channel1
Trigger Level(s)
Channel1 = 100.000 mV (noise reject OFF)
HoldOff = 40.000 ns

Figure C-35. Measurement of Component A Waveform on Panel TTC#13.

Filename: TC5#13AC.RAW
Date: 01-20-1995
Time: 15:21:49

Action Integral(Channel 1) = ~~.6878889~~

Charge Integral(Channel 1) = .6361679 (20)(13.16A/V) = 167 C

Quick-Look Plot from HP54200A
GPIBaddress 11 Channel 1

Channel [1] ___________________Status: Acquisition Complete____
LLO MTA

Range 3.0 V
Offset 1.000 V

Auto Scale [Disabled]
Store Mode [Normal]
Coupling [dc] [1:1]

Graph [1] 375 mV/div 1.00 V 200 ms/div -200.0 ms

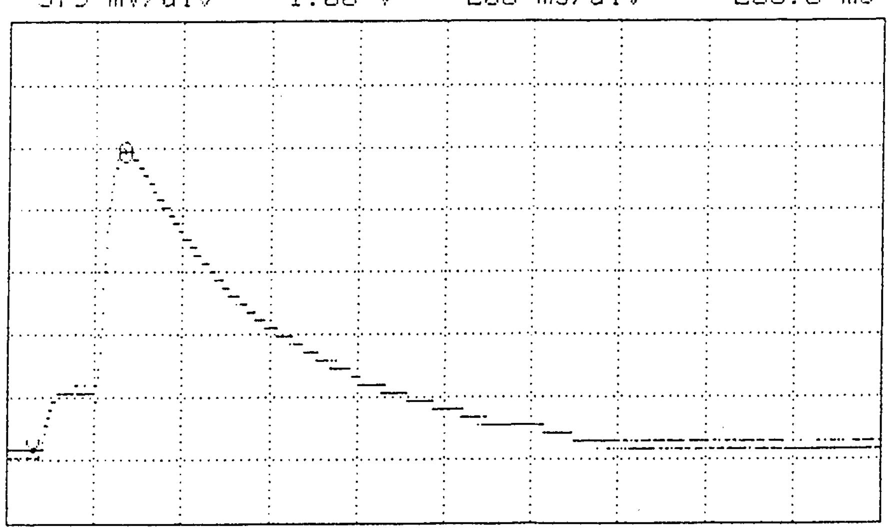
1:

Cursor 0

V_x -64.5 mV
T_x -140.0 ms

V_o 1.73 V
T_o 68.00 ms

ΔV 1.79 V
ΔT 208.0 ms



I_p = 471 A

Figure C-36. Measurement of Component C Waveform on Panel TTC5#13.

APPENDIX D

REFERENCES

REFERENCES

1. MIL-STD-1757A: Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware, 20 July 1983.

2. "Hazardous Test Procedures For High Energy Lightning Simulator (HELS)", AMSMI-RD-S-H-6.

APPENDIX E

ABBREVIATIONS

ABBREVIATIONS

A	Ampere
A^2	Ampere 2
C	Coulumb
E^3	Electromagnetic Environmental Effects
HELS	Hazardous Effects Lightning Simulator
kA	kilo Ampere
kV	kilo Volt
MCC-1	Marshall Convergent Coating -1
µF	MicroFarad
mm	Millimeter
µs	Microsecond
msec	Millisecond
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PC	Personal Computer
RTTC	Redstone Technical Test Center
TPS	Thermal Protection System
USBI	United Space Boosters Inc.
UTC	United Technologies Corporation
v	Volt

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